

## ABSTRACT

COBB, CHESTER RAY. Estimating nitrogen efficiency of swine lagoon liquid applied to field crops using continuously variable irrigation. (Under the direction of Robert L. Mikkelsen).

Application of anaerobic swine (*Sus scrofa domestica*) lagoon liquid onto cropland by irrigation is a common method of waste disposal and treatment. Currently, the application rate of swine lagoon liquid is based on the N concentration of the lagoon liquid and the N required by the receiver crop to obtain a realistic yield. In North Carolina, only 50% of the total N in the swine lagoon liquid applied by irrigation is considered available for plant use during the first year after application. Uncertainty exists as to whether this coefficient accurately predicts the amount of plant-available N. Therefore, research was conducted in the Coastal Plain of North Carolina to determine the efficiency of N uptake by corn (*Zea mays* L.) and soybean (*Glycine max* Merrill) receiving swine lagoon liquid through irrigation. The line-source sprinkler irrigation method was used to provide a continuous variable N rate, ranging from 0 to 290 kg N ha<sup>-1</sup>, across the field during 1999 and 2000. Ammonia volatilization losses ranged from 6 to 22% during irrigation. Crop yield and grain N recovered were affected more by the amount of liquid than N applied in 1999. Nitrogen recovered in grain in 1999 was <15% for both corn and soybean at 168 kg N ha<sup>-1</sup> of either swine lagoon liquid or NH<sub>4</sub>NO<sub>3</sub>. In 2000 at the 168 kg N ha<sup>-1</sup> rate, grain N removal by corn, nonnodulating soybean, and nodulating soybean was 28, 25, and 39% from swine lagoon liquid and 45, 31, and 56% from NH<sub>4</sub>NO<sub>3</sub>. Based on yields and grain N removed by corn and nonnodulating soybean in 2000, N from applied swine lagoon

liquid, accounting for N losses during irrigation, was about 70% as effective as  $\text{NH}_4\text{NO}_3$ . Symbiotic  $\text{N}_2$  fixation by the soybean was reduced by 60% when applied N reached  $175 \text{ kg N ha}^{-1}$  for both  $\text{NH}_4\text{NO}_3$  and swine lagoon liquid. While nodulating soybean removed more grain N than did either corn or nonnodulating soybean in 2000, soil inorganic N concentrations at the end of the growing season were higher for the nodulating soybean. Therefore, it is not conclusive if soybean would be a better receiver crop than corn for swine lagoon liquid. Based on the results of this study, using the 50% available N coefficient of the lagoon liquid comes close to predicting plant-available N when N losses during irrigation are around 25%. Nitrogen losses during irrigation can significantly affect plant-available N when applied N is based on the N concentrations of the lagoon liquid.

**ESTIMATING NITROGEN EFFICIENCY OF SWINE LAGOON  
LIQUID APPLIED TO FIELD CROPS USING CONTINUOUSLY  
VARIABLE IRRIGATION**

by

**CHESTER RAY COBB**

A thesis submitted to the Graduate Faculty of  
North Carolina State University  
in partial fulfillment of the  
requirements for the Degree of  
Master of Science

**SOIL SCIENCE**

Raleigh

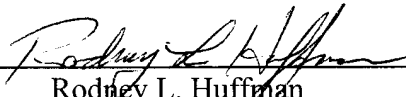
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## **BIOGRAPHY**

Chester Ray Cobb was born in Windsor, North Carolina on November 13, 1963. While growing up, he spent a lot of time with his grandparents (William and Ruby White) who lived on a small farm in Bertie County, North Carolina. It was with his grandparents that the author was introduced to growing crops such as corn, soybeans, peanuts, and tobacco and raising animals (pigs and chickens). He continued to help out on the farm until 1982 when graduated from Bertie Senior High School. Upon graduation from high school, the author attended the Agricultural Institute at North Carolina State University (NCSU) in Raleigh, North Carolina. After graduating from the Agricultural Institute in May 1984 with an Associate of Arts degree in General Agriculture, he proceeded to obtain a Bachelor of Science degree in Agronomy at NCSU. In December 1988, he graduated from NCSU and proceeded to work in the Soil Science Department at NCSU as an Agricultural Research Technician under Dr. Michael T. Hoover. Working under Dr. Hoover, the author gained valuable experience about the Cooperative Extension Service and all he ever wanted to know about septic systems. Having dreamt of being an Extension Agent, he decided to pursue a Masters of Science in Soil Science in August 1999. The author was grateful to be able to get back to his agricultural roots and to work under the direction of Dr. Robert Mikkelsen.

## **ACKNOWLEDGEMENTS**

As I have endeavored the rigors of research and education in the pursuit of a Master of Science degree, I have been blessed in so many ways that I know I will forget something or even worse, somebody. First of all, I must give all glory and praise to God for He has always been there for me, leading the way when I have allowed Him to. Secondly, I am very grateful to Dr. John L. Havlin and the Soil Science Department at North Carolina State University for granting me a research assistantship so I could pursue a Master of Science degree. Without the financial support, I could not have returned to school on a full time basis. Also, I am very grateful for the guidance and encouragement from my advisor, Dr. Robert Mikkelsen. Not only did he guide me, but he also helped with the fieldwork. I am also thankful for Dr. Rod Huffman and his guidance with the irrigation design and Dr. Larry King for his input concerning the field design and measurement of residual soil N. Also, worth mentioning is Dr. Dan Israel who provided vital assistance for measuring the response of soybean to SLL additions.

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## LIST OF ABBREVIATIONS

| Abbrev.                       | Meaning   |
|-------------------------------|---|
| C <sub>2</sub> H <sub>2</sub> | Acetylene   |
| C <sub>2</sub> H <sub>4</sub> | Ethylene  |
| NCCES                         | North Carolina Cooperative Extension Service                                      |
| NSB                           | nonnodulating soybean   |
| NUE                           | nitrogen use efficiency   |
| PAN                           | plant-available nitrogen  |
| SB                            | nodulating soybean  |
| Section 1                     | received only swine lagoon liquid   |
| Section 2                     | received both swine lagoon liquid and water                                       |
| Section 3                     | received NH <sub>4</sub> NO <sub>3</sub> treatments and variable amounts of water |
| SLL                           | swine lagoon liquid   |
| SPAD                          | Soil Plant Analysis Development (chlorophyll meter unit of measurement)           |
| Tg                            | teragram (10 <sup>12</sup> g)   |



# CHAPTER 1

## GENERAL INTRODUCTION

North Carolina is recognized as one of the leading swine (*Sus scrofa domesticus*) producing states in the nation. In 1999, receipts from swine production were second to broilers in North Carolina with approximately \$1.2 billion generated (NASS, 2000). As the revenue from swine production has increased, swine farms have grown in size while decreasing in number. In North Carolina, approximately 640 of the 3,680 swine farms accounted for 76% of the hogs and pigs inventory in 2000 (North Carolina Agriculture and Consumer Services, 2001). The trend to fewer and larger swine farms has been influenced by the integration and specialization of swine production in the United States (Mikkelsen, 2000).

While integration and specialization of swine farms have improved production efficiencies (McBride, 1995), other issues such as animal welfare and waste management have received more attention. A major concern for waste management has been the amount of waste generated within a localized area. While swine manure is a valuable fertilizer for crop production, the amount of waste generated may provide more nutrients than crops grown on the farm can utilize. The value of swine manure is reduced as distance from the source increases due to handling difficulties, transportation costs, and the availability of relatively inexpensive inorganic fertilizers.

For swine farms, anaerobic lagoons are commonly used for handling and treating wastes because they provide a simple and relatively inexpensive means of treatment on site (Andreadakis, 1992). Approximately 80% of swine and dairy farms in

Alabama use some type of lagoon system (Liu et al., 1995). In North Carolina, 85% of the swine farms utilize some type of lagoon system for waste treatment (Barker and Zublena, 1995).

Anaerobic lagoons provide partial waste treatment by reducing nutrient content and biological activity prior to land application. Within an anaerobic lagoon, some of the organic matter is converted into methane. As methane and other organic gases diffuse into the atmosphere from the lagoon, the  $O_2$  demand is reduced by 75 to 85% (Mikkelsen, 2000). Nitrogen is removed from the anaerobic lagoon liquid through  $NH_3$  volatilization. Mikkelsen (1997) estimated volatilization losses to be as high as 50 to 75% of the N entering the lagoon. Much of the P entering the lagoon settles with the sludge at the bottom. While some waste treatment occurs in the lagoon, the liquid is often further treated by disposal onto cropland.

Anaerobic swine lagoon liquid (SLL) is often applied to cropland by irrigation for disposal and treatment. In North Carolina today, land applications of anaerobic SLL are based supplying agronomic rates of N. Not all of the N within the SLL will be available for crop utilization. Plant-available nitrogen (PAN) is a term that refers to the estimated amount of N from an organic source that will be available to the plant. The calculated amount of PAN is critical for producing a realistic crop yield with minimal impacts on the environment. In determining PAN, an understanding of the N source, application method, and N transformations that occur during and after application is needed. The following sections will focus on the N content of anaerobic SLL and the fate of N from SLL applied to field crops by irrigation.

## **Nitrogen Content of Anaerobic Swine Lagoon Liquid**

Nitrogen concentrations of anaerobic swine lagoons vary depending on animal factors (breed, age, size, gender, etc.), housing environment, and feed composition (Mikkelsen, 2000). From three similarly operated swine lagoons, Wilhelm et al. (1980) found total N concentrations ranged from 309 to 938 mg N L<sup>-1</sup>. While total N concentrations vary between lagoons, research has indicated that the majority of the N is in the inorganic form. Zublena et al. (1990) estimated that out of 60 kg ha-cm<sup>-1</sup> (136 lb acre-inch<sup>-1</sup>) of total N for anaerobic SLL, 80% of the total N is present as NH<sub>4</sub><sup>+</sup>. Chescheir et al. (1985) reported NH<sub>4</sub><sup>+</sup>-N concentrations from SLL that were 82 and 92% of the total N. Other research (Westerman et al., 1995; Evans et al., 1984; Safley et al., 1992) has reported that 70 to 90% of the N in SLL is present in ammoniacal forms. While these concentrations can be used for N estimates from anaerobic swine lagoons, laboratory analysis of the SLL is needed for accurate N determinations on individual farms.

## **Plant Uptake**

Skarda (1977) reported that the N effectiveness of liquid manures was 40 to 90% of commercial fertilizers, depending on soil type and the time of application. Generally, previous research has demonstrated that plant uptake of N within agricultural systems is often less than 50% of applied fertilizer N (Sims, 1995; Wiesler, 1998). Wiesler (1998) and Peoples et al. (1995) have summarized research concerning the N uptake efficiencies of various crops receiving different inorganic N fertilizers.

Coastal bermudagrass (*Cynodon dactylon* L. Pers.) is often used as a receiver crop for SLL applications because its high nutrients requirement (NCCES, 1997). Burns et al. (1990) applying SLL to bermudagrass at 1, 2, and 4 times recommended N rates ( $335 \text{ kg ha}^{-1}$ ), reported plant N recoveries of 72, 74, and 44% respectively. In another experiment, bermudagrass removed about 60% of the applied N ( $435 \text{ kg ha}^{-1}$ ) from SLL (Westerman et al., 1995). Finally, when SLL was applied by irrigation to tall fescue (*Festuca arundinacea* L. Schreb) for 4 years at approximately 600 and 1,200  $\text{kg N ha}^{-1} \text{ yr}^{-1}$ , plant N removal at the end of the 4 years accounted for 64 and 35% of the total N applied respectively (Westerman et al., 1987).

Pathways of N loss, mainly  $\text{NH}_3$  volatilization, denitrification, and  $\text{NO}_3^-$  leaching, lower plant uptake of applied N (Wiesler, 1998). In an experiment in Indiana, Sutton et al. (1995) compared corn utilization of applied N from equivalent rates of swine manure and anhydrous  $\text{NH}_3$  injected into 4 different soils. Similar corn yields were obtained with equal rates of swine manure and anhydrous  $\text{NH}_3$  for all soils when a nitrification inhibitor was added to the swine manure. Sutton et al. (1995) believed that by stabilizing the N from the manure, N losses through leaching and denitrification were minimized, thus allowing for increased corn N uptake. They concluded that soils differ in their ability to retain applied N for crop production based on soil properties favorable for N transformations and losses to the atmosphere or water. Therefore, understanding N transformations and potential N loss pathways are important when applying SLL to cropland.

## Mineralization

Mineralization is important because it is the process by which organic forms of N are converted to inorganic  $\text{NH}_4$ . This reaction requires heterotrophic soil microorganisms that use the organic N compounds as an energy source for their metabolism. For optimum mineralization within the soil, a temperature range of 40 to 60 °C and a moisture content that is 50 to 75% of the soil's water holding capacity is required (Sims, 1995). Given optimum environmental conditions, the amount of C in respect to the amount of N present generally determines the rate of mineralization.

Flowers and Arnold (1983) evaluated the effects of adding 100  $\mu\text{g NH}_4^+\text{-N g}^{-1}$  soil as pig slurry on mineralization of soil N at different temperatures and soil moisture contents. In all cases but one, the mineralization rate of the slurry-treated soil was not significantly greater than the untreated soil within 175 days. While the addition of pig slurry did not increase the mineralization rate of soil N, there was evidence that organic N from the slurry contributed to the overall mineralized N amount. Aho (1996) in a laboratory experiment examining the mineralization of SLL in different soils from the Coastal Plain of North Carolina, reported that 100% of the applied N was recovered by 57 days after the SLL had been incorporated into a sandy loam soil. When the SLL was surface applied, approximately 100% of the applied N was recovered from a loam as compared to 20% from a loamy sand after 42 days. Aho (1996) observed that the nitrification rate was slower for the loamy sand than loam. Application method (incorporated versus surface applied) was a major factor influencing N transformations.

## **Nitrification**

The oxidation of  $\text{NH}_4^+$  to  $\text{NO}_3^-$  by autotrophic and heterotrophic bacteria is referred to as nitrification. Assuming a sufficient population of nitrifying bacteria, the amount of  $\text{NH}_4^+$  present, soil pH, presence of  $\text{O}_2$ , soil moisture, and temperature are the primary factors influencing nitrification rates. Generally, environmental conditions capable of supporting crop growth are also favorable for nitrification. Xu et al. (1998) used irrigation to apply SLL to corn in order to validate a computer model prediction of daily  $\text{N}_2\text{O}$  emissions. The highest  $\text{N}_2\text{O}$  emission rates occurred one day after SLL application. Because the amounts of  $\text{N}_2\text{O}$  emitted were proportional to the amounts of  $\text{NH}_4^+$  in the SLL, they determined that  $\text{N}_2\text{O}$  emissions within one day after application were released by nitrification. This suggests that  $\text{NH}_4^+$  added to the soil can be nitrified within a few days after application under favorable conditions.

## **Volatilization**

Ammonia volatilization and denitrification are pathways of gaseous N losses to the atmosphere. Because of the high  $\text{NH}_4^+$  content of SLL,  $\text{NH}_3$  volatilization tends to be high for SLL applied by irrigation. The extent of  $\text{NH}_3$  volatilization is determined by the difference in  $\text{NH}_3$  partial pressure between the ambient atmosphere and that in equilibrium with the solution (Peoples et al., 1995). The  $\text{NH}_4^+$  concentration, solution temperature, and pH of the effluent or soil solution are important factors that affect the partial pressure of  $\text{NH}_3$  and thus  $\text{NH}_3$  volatilization.

Obviously, materials with higher  $\text{NH}_4^+$  concentrations have the potential for greater  $\text{NH}_3$  losses. Ammonia volatilization is also enhanced with increases in the

temperature of the solution. As temperature increases, the relative proportion of  $\text{NH}_3$  to  $\text{NH}_4^+$  at a given pH increases (Peoples et al., 1995). This shift in temperature decreases the solubility of  $\text{NH}_3$  in water and allows for greater  $\text{NH}_3$  diffusion into the atmosphere.

Ammonia volatilization is also enhanced with increases in the pH of the solution. The equilibrium between  $\text{NH}_4^+$  and  $\text{NH}_3$  in solution is affected by the pH of the solution. As pH increases from 6 to 7, 8, and 9, the relative  $\text{NH}_3$  concentration increases from 0.1 to 1, 10, and 50% respectively (Peoples et al., 1995). Higher  $\text{NH}_3$  concentrations potentially lead to increased  $\text{NH}_3$  volatilization. Pote et al. (1980) in an experiment evaluating  $\text{NH}_3$  losses during sprinkler application of SLL predicted  $\text{NH}_3$  losses to be  $\leq 8\%$  when the pH of the SLL was near neutral (7 to 8). At a pH of 10.5, they estimated  $\text{NH}_3$  losses of 30 to 60% for sprinkler irrigated SLL. Pote et al. (1980) also evaluated  $\text{NH}_3$  losses during sprinkler irrigation of SLL considering the size and flight of a spray droplet. They noticed that  $\text{NH}_3$  losses from SLL at pH 10.5 were  $< 50\%$  when droplet diameter was  $> 2$  mm and  $> 50\%$  when droplet diameter was  $< 2$  mm.

Various amounts of  $\text{NH}_3$  volatilization during sprinkler irrigation of SLL have been reported. Burns et al., (1987) evaluated SLL applications to tall fescue and observed that  $\text{NH}_3$  losses from nighttime sprinkler irrigation events averaged 10% during the spring and 22% during the summer. In another study using nighttime sprinkler irrigation, Humenik et al. (1976) reported a  $\text{NH}_3$  loss of 25% during application of SLL. They expected that applied N losses would be greater for daytime than nighttime irrigation events because of higher temperatures and wind velocities. Safley et al. (1992) applied SLL during the daytime using a center pivot irrigation system and calculated that 14 to 37% of the total N applied was lost as  $\text{NH}_3$ . While a

slight decrease in  $\text{NH}_3\text{-N}$  concentrations between the liquid collected during irrigation and the lagoon liquid was noticed, they determined that volumetric losses during irrigation accounted for 62 to 100% of the  $\text{NH}_3$ . Evaporation and droplet drift lowered the amount of liquid collected during irrigation.

Not only is  $\text{NH}_3$  lost during irrigation, but it is also lost from the surface of plants and the soil after SLL applications. No research was found documenting  $\text{NH}_3$  losses from the surface of plants after SLL applications. Volatilization of  $\text{NH}_3$  from the soil is affected by crop cover and application method. Peoples et al. (1995) reported that  $\text{NH}_3$  losses ranged from 9 to 33% of the fertilizer N when applied to grasslands and range from negligible to >50% when applied to upland and lowland cropping systems. Hoff et al. (1981) found that injection of liquid swine manure led to lower  $\text{NH}_3$  losses from the soil when compared to broadcast applications of liquid swine manure. When liquid swine manure was injected into the soil at rates of 205 and 409 kg  $\text{NH}_4\text{-N ha}^{-1}$ , 2.5% of the total applied N was lost as  $\text{NH}_3$ . On the other hand, when liquid swine manure was surface applied at the same rates, the amount of  $\text{NH}_3$  lost was 14 and 11.2% respectively. Sharpe and Harper (1997) measured  $\text{NH}_3$  losses totaling 82% from SLL applied to oat (*Avena sativa*) by irrigation, of which 69% was  $\text{NH}_3$  volatilization from the soil. Based on previous research data concerning  $\text{NH}_3$  losses during irrigation of SLL and afterwards from the soil, volatilization can be a major pathway for N loss.



## Denitrification

The reduction of  $\text{NO}_3^-$  and  $\text{NO}_2^-$  into  $\text{NO}$ ,  $\text{N}_2\text{O}$ , and  $\text{N}_2$  is referred to as denitrification. Anaerobic conditions are required for denitrification to occur. The amount of  $\text{O}_2$  present in the soil is primarily controlled by soil texture, structure, and moisture content. Generally, denitrification can occur at soil moisture contents  $> 60\%$  of the pore space (Peoples et al., 1995). Other factors influencing denitrification are pH, temperature, and the amount of soluble organic C. The pH and temperature range required for most field crops is favorable for denitrification. Soluble organic C is required to provide the energy source and electrons for the reducing bacteria.

Peoples et al. (1995) reported denitrification losses ranging from 2 to 9% when N fertilizer was applied to a well-drained sandy loam soil. When N fertilizer was applied to a poorly drained sandy loam soil, denitrification losses ranged from 6 to 30%. Thompson et al. (1987) recorded denitrification losses of 12 and 2% for cattle slurry N surface applied to grassland when applied in December and April respectively. Over a period of 15 days starting at the first irrigation event and ending one day after the last irrigation event, Sharpe and Harper (1997) measured  $\text{N}_2\text{O}$  emissions that accounted for about 13% of total N additions from three applications of SLL onto oats. No attempt was made to determine what percentage of the  $\text{N}_2\text{O}$  emissions were derived specifically from denitrification or nitrification.

Denitrification has been studied in the Coastal Plain of North Carolina as a mechanism for removing excess N in the subsoil from cropland before it moves into an aquifer or surface waters. Gambrell et al. (1975) evaluated the denitrification potential within the subsoil of a moderately well-drained and poorly drained soil. Denitrification

was found to be the major mechanism for  $\text{NO}_3\text{--N}$  loss in the poorly drained soil compared to leaching for the moderately well-drained soil. Favorable conditions for denitrification were found in the poorly drained soil from 1.2 to 2.1 m below the soil surface throughout the year. The water table generally ranged from 0.3 to 0.6 m below the surface for the poorly drained soil during the winter and early spring and generally remained below 3.5 m for the moderately well-drained soil. Evans et al. (1995) summarized studies examining the impacts of different drainage systems on surface water quality in the Coastal Plain of North Carolina. They reported that in some cases  $\text{NO}_3\text{--N}$  concentrations were reduced by 10 to 20% in the outflow from controlled drainage (allows shallow water table management) as compared to conventional drainage (only promotes water movement away from the field). Denitrification was believed to be the major pathway for the loss of  $\text{NO}_3\text{--N}$  in those cases. Kliever and Gilliam (1995) reported higher denitrification rates as the water table was maintained nearer to the soil surface. The majority of denitrification occurred within 36 to 54 cm of the soil surface when the water table was maintained at either the 30 or 45 cm depth. When the water table depth was maintained at 15 cm, denitrification shifted from the 36 to 54 cm zone to the 18 to 36 cm zone as  $\text{NO}_3\text{--N}$  was depleted at the lower depth. Therefore, denitrification losses from SLL applications to cropland may be greater for soils with a high water table than well-drained soils in the Coastal Plain of North Carolina.

## Leaching

Leaching is the process by which nutrients are lost as water percolates through the soil profile. Nitrate is susceptible to leaching because it is an anion and is not attracted to the cation exchange sites in the soil. Leaching of  $\text{NO}_3^-$  to the aquifers or to surface waters such as rivers and lakes is a concern for several reasons (NCCES, 1997; Westerman et al., 1995). The maximum allowable concentration for  $\text{NO}_3^-$  in drinking water is 10 ppm or  $\text{mg L}^{-1}$   $\text{NO}_3\text{-N}$  as established by the United States Public Health Service (1962). Eutrophication may become a problem when nutrients, such as N, are present in excessive concentrations in surficial waters (NCCES, 1997).

Most studies have documented  $\text{NO}_3\text{-N}$  accumulations in soil profiles at excessive manure application rates (King et al., 1990; Westerman et al., 1995; Westerman et al., 1987; Evans et al., 1984; Humenik et al., 1976). Patni (1995) showed that animal manure slurry applied at rates of  $500 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  to field crops for more than 4 years led to  $\text{NO}_3\text{-N}$  concentrations  $>10 \text{ mg L}^{-1}$  in subsurface drainage waters. These concentrations persisted for several years after applications had stopped. Similar  $\text{NO}_3\text{-N}$  concentrations have also been found in the shallow groundwater below agricultural fields receiving inorganic fertilizers (Evans et al., 2000). When SLL was applied at recommended rates to coastal bermudagrass grown on a sandy soil, Westerman et al. (1995) found that three sampling wells outside of the plots had  $\text{NO}_3\text{-N}$  concentrations above  $10 \text{ mg L}^{-1}$ . In another study applying SLL to Coastal bermudagrass at application rates 1:2:4 times the recommended amount (325, 650 and  $1,300 \text{ kg N ha}^{-1}$ ), Evans et al. (1984) reported subsurface drainage concentrations of 6, 18, and  $27 \text{ mg NO}_3\text{-N L}^{-1}$  respectively. Soil cores taken within the plots receiving the

highest application rate showed  $\text{NO}_3\text{-N}$  concentrations increasing from about 5 to 20  $\mu\text{g g}^{-1}$  as soil depth increased from 0 to 90 cm. Soil cores taken 1.8 m downslope from the plots showed  $\text{NO}_3\text{-N}$  increasing up to about 10  $\mu\text{g g}^{-1}$  to a soil depth of 90 cm. Sloan et al. (1999) found elevated  $\text{NO}_3^-$  concentrations in the shallow groundwater beneath a bermudagrass spray field. The pasture had been used for a spray field for about 20 years and during the study received approximately 350 to 400  $\text{kg N ha}^{-1} \text{ yr}^{-1}$ . Occasionally, concentrations in excess of 40  $\text{mg NO}_3\text{-N L}^{-1}$  were found in wells immediately adjacent to the nearby stream. It appears that significant leaching of  $\text{NO}_3^-$  occurs when excessive amounts of SLL are applied onto agricultural fields and when a spray field receives annual applications of SLL for many years. These same trends could also be expected from N fertilizer when applied in excess of the plant requirement.

### **Runoff**

Runoff is affected by factors such as method of SLL application, soil characteristics, and rainfall intensity. If runoff occurs during the irrigation event, waste constituents can be transported off site. Humenik et al. (1976) reported that runoff during irrigation contained 50 to 80% of the nutrient concentrations from the lagoon. In this case, a grass buffer strip surrounded the field and runoff from irrigation events infiltrated the soil surface within 1.5 m of the field edge. Runoff from rainfall events after application contained <5% of all applied waste nutrients. Measuring N concentrations in rainfall runoff from a tall fescue field irrigated with SLL, Westerman et al. (1987) reported N losses ranging from 0.5 to 1.3% of the N applied. With this

study, the months with the highest rainfall had the highest runoff. Finally, Westerman et al. (1985) reported that the greatest potential for high concentrations of waste constituents in runoff is during irrigation events and when irrigation occurs during rainfall events. Increasing application rates of SLL had little effect on the quantity runoff. In most of the cases above, irrigation rates were applied to supply a certain amount of N. No consideration was given to rainfall in respect to irrigation events. As a result, irrigation events sometime occurred during rainfall events or even when rain was predicted. Thus, with proper irrigation management, N losses through runoff can be controlled.

### **Immobilization**

Immobilization is the reverse of mineralization and it involves the assimilation of inorganic N by soil microbes into organic compounds that constitute microbial biomass. Nitrogen is immobilized as a microbial population grows to decompose organic matter (C). Optimum soil conditions for immobilization are similar to those required for mineralization (Sims, 1995). Of the physical and chemical properties of the organic waste, the C to N ratio (C:N) is one of the most important factors in predicting immobilization. Sims (1995) reported that organic wastes with high C:N ratio ( $C:N > 25:1$ ) provide high-energy sources for microbes causing immobilization of the inorganic N.

Flowers and Arnold (1983) conducted an incubation study looking at immobilization and mineralization of N in pig slurry over a range of temperatures and moisture contents. While the time period of net immobilization was shorter with

temperatures  $>5^{\circ}\text{C}$ , there were no differences in N amounts immobilized over the range of temperatures ( $5 - 30^{\circ}\text{C}$ ) tested. Overall, they reported that net immobilization occurred within 30 days after application and approximately 40% of the  $\text{NH}_4\text{-N}$  in the pig slurry was immobilized. In a study looking at SLL applied to bermudagrass hay fields, Aho (1996) recorded a higher potential for N immobilization in the pasture with a loam texture than the pasture with a loamy sand texture. Ammonium concentrations in the loamy sand soil increased by 51% of the applied N compared to about 10% for the loam after SLL application. The increased immobilization potential for the loam was related to higher dissolved organic C concentrations found in the loam than the sandy loam. Thus, the amount of N immobilized is highly influenced by the C:N ratio of the material and the amount of C in the soil. Since SLL has a low C:N ratio, approximately 0.5:1 (Barker et al., 1994), the soil properties of the spray field would have the largest effect on the rate of immobilization.

### **Conclusions**

Swine lagoon liquid appears to be a good source of N for crop production. However, the fate of N in SLL, when applied by irrigation, is hard to predict. Plant uptake, volatilization, denitrification, mineralization, nitrification, leaching, runoff, and immobilization affect the fate of N added in SLL. These reactions are affected by many factors such as pH, temperature, N form (inorganic or organic), soil moisture content, crop, and irrigation management. Because these factors change from one field to another, a single estimate of PAN that can be universally applied is difficult to determine.

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## **CHAPTER 2**

### **CONTINUOUS VARIABLE NITROGEN APPLICATIONS OF SWINE LAGOON LIQUID ONTO FIELD CROPS USING THE LINE-SOURCE IRRIGATION TECHNIQUE**

#### **ABSTRACT**

**Application of anaerobic swine (*Sus scrofa domesticus*) lagoon liquid (SLL) to field crops by irrigation is a common means of treatment and disposal. The amount of SLL that can be applied to cropland is based on plant utilization of applied N. An experiment was designed to evaluate the N use efficiency of field crops irrigated with SLL using the line-source irrigation technique apply variable N rates. This study evaluated the predictability of the line-source irrigation technique to provide variable application of SLL. A double line-source was used to provide variable amounts of SLL and water to corn (*Zea mays* L.) and soybean (*Glycine max* Merrill). Random rows of catch cans were placed perpendicular to the irrigation lines and used to measure application amounts. Applied N from the SLL was determined by measuring the N recovered in the catch cans after irrigation. As expected, application amounts of N and water decreased as distance from the irrigation line increased. Application depths at given distances from the irrigation line were somewhat variable due to sprinkler spacings, as necessitated by the field dimension. The field area between the SLL and water lines received uniformly similar liquid application amounts. The line-source irrigation technique effectively delivered variable amounts of SLL and water to the field-scale experiment, which would have been unfeasible with other techniques.**

## INTRODUCTION

For most agronomic studies, crop response to essential plant nutrients is typically measured using 4 or 5 application rates of the nutrient in question. When the treatments are replicated and placed in a random block design, statistical analysis can show significant differences among treatments. However, the discrete treatments selected may not be appropriate for generating a response curve. The line-source irrigation technique incorporates continuously variable applications of the treatments with a relatively small land requirement.

The concept for the line-source irrigation technique originated from a continuous function experiment dealing with N fertilization of sweet corn (Fox, 1973). Individual plants were fertilized with urea from 0 to 220 kg ha<sup>-1</sup> in 5.5 kg ha<sup>-1</sup> increments. With this design, the N level increased in small increments in one direction. Fox suggested that a second factor such as irrigation could be added to the study interactions. In this case, the first factor is varied in one direction while the second factor is varied perpendicular to the first. A concern with Fox's design was that plot size consisted of a single corn plant.

Bauder et al. (1975) used the concept suggested by Fox and designed a study where N application rates were placed at 90° angles to varied water levels. The varied water amounts were applied using drip irrigation to provide a high degree of control. It was noted that this type of field design provided a better visualization of the crop production surface because no buffer area is needed around each treatment due to the incremental change between treatments. Unfortunately, this system proved to be quite expensive and required considerable manpower to operate.

Hanks et al. (1976) designed a field irrigation study to obtain a continuously variable application pattern. This research design became known as the “line-source” sprinkler irrigation system. Very simply, this design involved a single line of sprinklers down the center of the plot (Fig. 2.1). Hence the identifier “line-source” was coined. To obtain the continuous “triangular” application pattern as a function of distance from the line-source, it was suggested that the sprinklers be spaced at 10% or less of the wetted diameter. This type of sprinkler spacing allowed for greater uniformity at application levels parallel to the line. However, often it is desirable to use wider sprinkler spacings due to material costs and the high application rates next to the line. It was suggested that sprinkler spacings up to 20 to 25% of the wetted diameter are reasonable as long as the variations in application depths parallel to the line do not exceed  $\pm 10\%$  of the mean. Some of the limitations Hanks et al. (1976) observed with this research design were the distortions of sprinkler patterns due to wind speeds  $\geq 3 \text{ km h}^{-1}$ ), no variation in irrigation frequency allowed due to the structured irrigation levels, and problems with ponding or runoff that may occur at the highest application rates.

Due to the lack of guidelines for sprinkler selection, Willardson et al. (1987) evaluated different commercially available sprinklers for their potential use in line-source experiments of a specific plot size. They developed a computer program to evaluate any given sprinkler for use in a line-source experiment based water volumes collected in catch cans arranged in four radial lines. Overlap profiles are generated for the area between two adjacent sprinklers at various sprinkler spacings. From the output, the user can select the sprinkler spacing providing the highest uniform application. Generally, the highest application uniformity at any distance parallel to the line-source

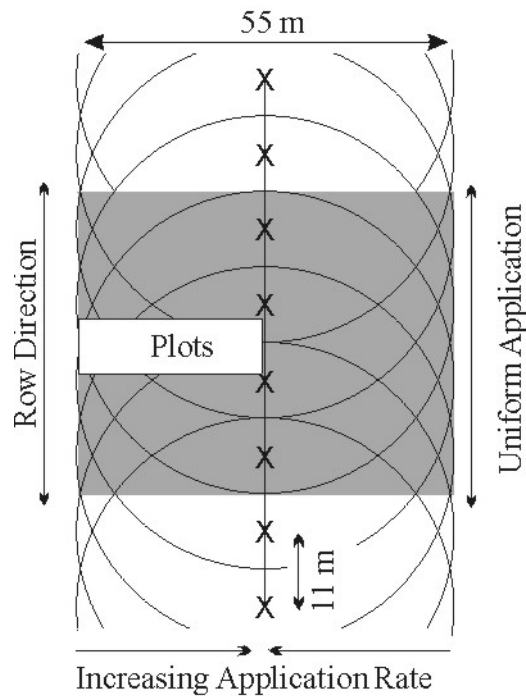


Fig. 2.1. An example of a line-source sprinkler irrigation system design using a sprinkler with a wetted diameter of 55 m and a sprinkler spacing 20% of the wetted diameter.

is obtained as sprinkler spacing decreases. While uniformity is desired, the application rate may exceed the infiltration capacity of the soil when sprinklers are spaced closer together.

Another consideration for designing an experiment using the line-source concept involves statistical analysis of the results (Bauder et al., 1975; Hanks et al., 1980; Bresler et al., 1982). The difficulty stems from the nonrandom systematic irrigation applications leaving no valid estimate of error for the irrigation main effect or comparisons involving the irrigations effects (Hanks et al., 1980). In most cases

however, irrigation effects are large enough that statistical analysis is not as critical. For the randomly applied variables, an analysis of variance does provide a valid error term. Bauder et al. (1975) conducted an experiment to observe differences between results obtained from a continuously variable plot design and a randomized block, split block design. The results from each experiment led to basically the same conclusions. Using data from three different experiments, Bresler et al. (1982) reported on spatial techniques to address the statistical problems arising from the continuous variable water applications. They used scaled variograms to filter out the trend imposed by the variable water amounts, thus revealing the influence of other factors assumed to be homogeneous such as soil properties and experimental errors. For every experiment they analyzed, the scaled variograms revealed that the average crop response within an irrigation level was strongly dependent on the amount of water received at that location. Their analysis also revealed that soil properties could significantly influence the variability of crop responses measured.

Because of the inherent water gradient, the line-source irrigation technique has been used in studies determining the impact of water management on crop production. Miller et al. (1980) used the line-source concept to determine the daily minimum irrigation in which sugar yields from sugarbeets (*Beta vulgaris* L.) would not be reduced on medium and coarse-textured soils. Singh and Singh (1996) applied various irrigation regimes at different growth stages of cotton (*Gossypium* sp.) to estimate the optimum irrigation schedule that would allow for better plant water utilization and minimize water losses through percolation. Gallardo et al. (1996) examined the effects of variable water supply on the water use, growth and yield of crisp head and romaine

lettuce (*Lactuca sativa* L.) cultivars. Recently, Guttieri et al. (2000) used the line-source technique to determine the effects of moisture stress on the final quality (protein content, flour yield, and bread making quality) of six hard red spring wheat (*Triticum aestivum* L.) cultivars.

Also, the line-source concept has been used to supply variable rates of another factor such as N while eliminating the water gradient. Lauer (1983) modified the line-source concept to provide a variable N application rate along with a uniform water application. This was accomplished by adding two additional irrigation lines, one to each side of the main line-source. The N gradient was produced by injecting N into the irrigation system and distributing it through the middle line of sprinklers. The outer lines were used to equalize the applied water amounts to either side of the middle line. Building upon the design used by Lauer (1983), Magnusson et al. (1988) designed a study to simultaneously evaluate linear gradients of water, salinity, and N on corn growth and development. Their design involved two perpendicular sets of three irrigation lines. The centerline of one set was used to apply the N gradient while the centerline of the other was used to apply the saline water gradient. They demonstrated that decreasing concentrations gradients from the line-source could be produced for two variables without varying the water.

Finally, other experiments have been designed to evaluate interactions of water and some other factor. Hanks et al. (1978) used the line-source concept to measure the interaction of irrigation rate and salinity on corn production. Sorensen et al. (1980) examined the effects of early season cultivation and variable irrigation on dry matter production and yield of corn. Stark et al. (1983), Beverly et al. (1986), and Meyer et al.



(1998) evaluated plant response to N and water from celery (*Apium graveolens*), broccoli (*Brassica oleracea* L.), and potato (*Solanum tuberosum* L.), respectively. All three of these studies determined water and N management needed for optimal vegetable production while minimizing the amount of N lost through leaching.

As documented, the line-source technique effectively provides variable gradients that can be used for many research applications. This present study adopts the line-source concept to provide variable applications of anaerobic SLL to field crops. Since the amount of N in the SLL is proportional to the liquid in the SLL, another line-source consisting of only water was added to eliminate the water gradient. The objectives of this study were to (1) determine sprinkler setup necessary for achieving variable SLL application amounts, (2) document SLL and water application amounts as distance from the irrigation line increased, and (3) determine the amount of N applied from the irrigated SLL.

## **MATERIALS AND METHODS**

Field research was conducted on the Upper Coastal Plain Research Farm near Rocky Mount, NC utilizing available equipment from the farm. A solid set irrigation system was utilized for the sprinkler tests and irrigation applications of SLL and water. General characteristics of the impact sprinklers considered for the continuously variable applications of SLL are listed in Table 2.1. Sprinklers were attached to 1.8 m risers for all tests and irrigation events. Water from a nearby pond on the research farm was used for the initial sprinkler tests and irrigation events. The SLL used for the final experiment came from a lagoon adjacent to the research field.

Table 2.1. Manufacturer performance data of impact sprinklers considered for utilization in the line-source irrigation technique.

| Sprinkler <sup>†</sup> | Nozzle Size <sup>‡</sup> | Nozzle Pressure | Wetted Diameter | Discharge Rate                 |
|------------------------|--------------------------|-----------------|-----------------|--------------------------------|
|                        | mm                       | kPa             | m               | m <sup>3</sup> h <sup>-1</sup> |
| 70CW-TNT               | 8.7                      | 276             | 40              | 4.8                            |
|                        |                          | 345             | 42              | 5.4                            |
|                        |                          | 414             | 44              | 5.9                            |
|                        |                          | 483             | 46              | 6.5                            |
|                        |                          | 552             | 47              | 6.9                            |
| 80E-TNT                | 9.5 x 5.6                | 414             | 48              | 9.4                            |
|                        |                          | 483             | 50              | 10.2                           |
|                        |                          | 552             | 52              | 11.0                           |
|                        |                          | 621             | 54              | 11.7                           |
|                        |                          | 690             | 55              | 12.4                           |
| 80EW-TNT               | 9.5                      | 414             | 48              | 7.0                            |
|                        |                          | 483             | 50              | 7.6                            |
|                        |                          | 552             | 52              | 8.1                            |
|                        |                          | 621             | 54              | 8.7                            |
|                        |                          | 690             | 55              | 9.2                            |
| 7525-1-1M              | 9.5                      | 276             | 41              | 5.5                            |
|                        |                          | 345             | 44              | 6.2                            |
|                        |                          | 414             | 47              | 6.9                            |
|                        |                          | 483             | 49              | 7.5                            |
|                        |                          | 552             | 52              | 8.1                            |

<sup>†</sup>Sprinklers 70CW-TNT, 80E-TNT, and 80EW-TNT are manufactured by Rain Bird. (Glendora, CA.). Sprinkler 7525-1-1M manufactured by Senninger (Orlando, FL.). Use of these specific sprinklers is not meant as an endorsement.

<sup>‡</sup>Sprinkler 80E-TNT has a 5.6 mm spreader nozzle.

### Sprinkler Tests

Tests were conducted under minimal wind conditions and followed the protocol set by ASAE (1998) for the testing of sprinkler distribution for research purposes. Eight transects of catch cans (92 mm diameter cups) were placed radially to the sprinkler at 45° angles. Each transect consisted of 10 catch cans spaced approximately 3 m apart. The liquid volume in each catch can was measured and converted to a depth

basis. The radial profile was determined to be the average application depth at specific distances from the sprinkler. Next, the radial profile for the selected sprinkler was entered into a computer program, designed by R. Huffman (Biological and Agricultural Engineering Dept., NCSU), which calculates and displays the overlapped application pattern for arbitrary head spacings. By inspecting the program outputs, the sprinklers and head spacing that would provide the desired variable application pattern were selected.

### **Experimental Design**

After sprinkler type and spacing had been selected, the field research plots were designed to fit sprinkler and field constraints (Fig. 2.2). A parallel water line-source was added to eliminate the water gradient from the SLL line-source. Based on the irrigation design, the field was divided into three blocks, 30 by 88 m each. Section 3 was increased by 6 m to provide a non-irrigated area. The area in which water and SLL applications overlapped was labeled as Section 2. Section 1 received only continuously variable SLL applications. Section 3 consisted of randomized fertilizer treatments with continuously variable water applications.

Full circle impact sprinkler model 80E-TNT was the main sprinkler used. For the last irrigation event in 1999, a part circle impact sprinkler (model 7525-1-1M) was used to provide more uniform coverage at the ends of both line-sources. Generally, the sprinklers were spaced 13 m apart. Pressure gauges were installed on selected risers to monitor head pressures along the irrigation lines. Irrigation pumps were operated to provide 690 to 760 kPa at the pump and 620 to 690 kPa at the sprinkler heads.

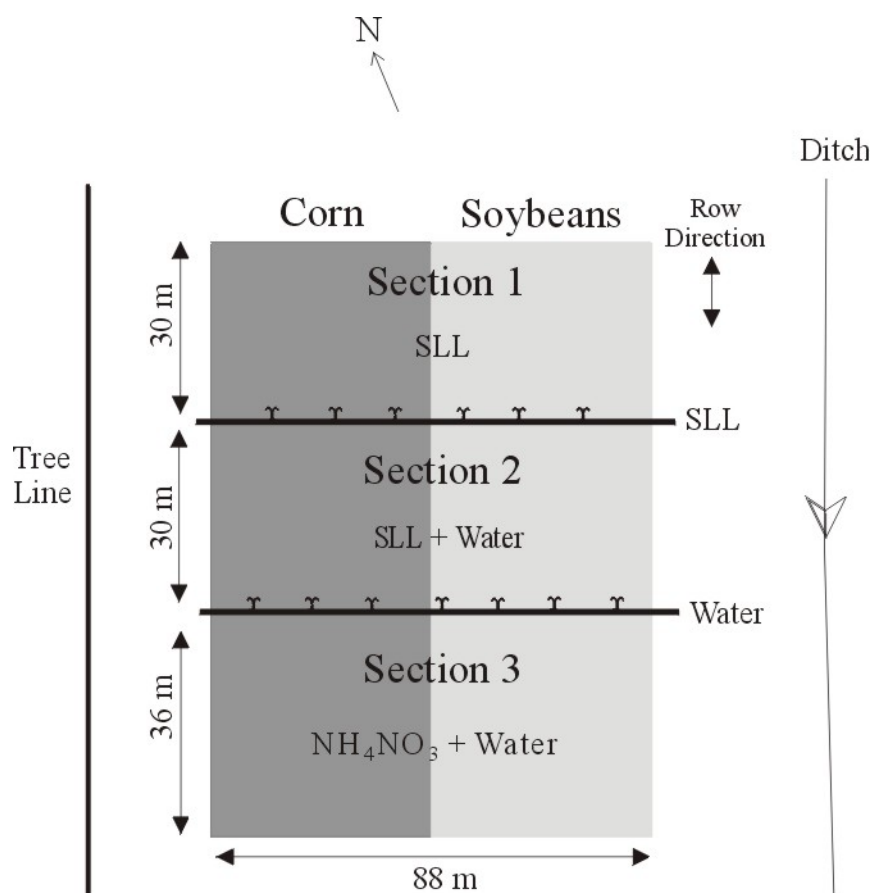


Fig. 2.2. Field layout of treatments at the Upper Coastal Plain Research Station (Field P7).

### Irrigation Events

Irrigation events were scheduled for early morning or early evening to limit evaporation and wind distortion of applications. In 1999, both SLL and water were applied at the same time. In 2000, SLL and water were applied separately within a 24-h period to limit runoff. The irrigation events were scheduled to supply N for crop utilization when soil moisture conditions allowed for irrigation. Each SLL irrigation event ran until water ponded on the soil surface. The run time for the SLL application determined the duration of the water application. For each application of SLL and

water, pump pressure, nozzle pressure, and wind speed were recorded periodically (Table 2.2).

For most irrigation events, 12 rows of 30 to 31 catch cans were placed in sets of three transects (along crop rows) perpendicular to the line-source. The first line of catch cans was in line with the centermost sprinkler with the other two lines placed 3 m and 6.1 m to the side of the sprinkler location. When a transect was in line with the sprinkler, the catch cans were spaced 1.5 m from the sprinkler and then every 3 m. The height of the catch cans was  $\approx 1.2$  m for soybean. For corn, average catch can height was  $\approx 1.2$  m in events A, D, and E and  $\approx 2.1$  m in events B, F, G, and H (Table 2.2). Maps of the irrigation distribution and variable N rate were generated in ArcView using the spline method to interpret the data.

### **Nitrogen Application Rates**

The amount of N applied from SLL and water applications was based on N concentrations of random liquid samples taken from catch cans immediately after irrigation. Liquid samples were also taken directly from the line-sources as the irrigation system depressurized to determine N concentrations pumped from the lagoon. After collection, the samples were placed in a cooler with ice and transferred to a refrigerator (4°C) until they could be analyzed for N. Total N was measured by the macro-Kjeldahl method (APHA, 1992) using  $\text{CuSO}_4$  as the catalyst to convert organic N into  $\text{NH}_3\text{-N}$ . Once the N was converted to the  $\text{NH}_3\text{-N}$  form, N was measured by distillation with boric acid followed by titration with potassium biiodate (APHA, 1992).

Table 2.2. Summary of sprinklers locations and application conditions for each irrigation event.

| Event <sup>†</sup> | Date         | Liquid Irrigated | Duration of Irrigation Run | Sprinklers Used | Sprinkler Locations <sup>‡</sup> | Pump Pressure | Sprinkler Pressure | Wind Speed <sup>§</sup> | Wind Direction |
|--------------------|--------------|------------------|----------------------------|-----------------|----------------------------------|---------------|--------------------|-------------------------|----------------|
|                    |              |                  | min                        |                 | Row #                            | kPa           | kPa                | m s <sup>-1</sup>       |                |
| A                  | 7 June 1999  | SLL              | *                          | 80E-TNT         | 16, 43, 70, 83                   | *             | *                  | 1.9–3.0                 | SW–WSW         |
|                    |              | Water            | *                          | 80E-TNT         | 9, 22, 36, 50, 63, 80            | *             | *                  |                         |                |
| B                  | 23 June 1999 | SLL              | 30                         | 80E-TNT         | 16, 43, 70, 83                   | 828           | 760                | 2.3–3.0                 | NE–ENE         |
|                    |              | Water            | 30                         | 80E-TNT         | 9, 22, 36, 50, 63, 80            | 828           | 690                |                         |                |
| C                  | 28 July 1999 | SLL              | 60                         | 80E-TNT         | 14, 20                           | 690           | 690                | 0.7                     | N              |
|                    |              | SLL              |                            | 7525-1-1M       | 48                               |               | *                  |                         |                |
|                    |              | Water            | 60                         | 80E-TNT         | (-5), 10, 23                     | 690           | 690                |                         |                |
|                    |              | Water            |                            | 7525-1-1M       | 50                               |               | 586                |                         |                |
| D                  | 18 May 2000  | Water            | 60                         | 80E-TNT         | 75                               | 760           | 760                | 4.2–5.1                 | SW             |
|                    |              | Water            |                            | 70CW-TNT        | 83                               |               |                    |                         |                |
|                    |              | Water            |                            | 7525-1-1M       | 49, 96                           |               | 690                |                         |                |
|                    | 19 May 2000  | SLL              | 60                         | 80E-TNT         | 75                               | 655           | 655                | 4.6–5.1                 | SW–WSW         |
|                    |              | SLL              |                            | 70CW-TNT        | 62                               |               |                    |                         |                |
|                    |              | SLL              |                            | 7525-1-1M       | 49, 96                           |               | 620                |                         |                |
| E                  | 2 June 2000  | SLL              | 40                         | 80E-TNT         | 22, 35, 49, 62, 76               | 620           | 620                | 1.6–2.2                 | WNW–NW         |
|                    |              | SLL              |                            | 7525-1-1M       | 2, 96                            |               | 620                |                         |                |
|                    | 3 June 2000  | Water            | 40                         | 80E-TNT         | 16, 29, 42, 55, 69, 83           | 690           | 590                | 1.1–3.9                 | N              |
|                    |              | Water            |                            | 7525-1-1M       | 2, 96                            |               | 590                |                         |                |
| F                  | 12 June 2000 | SLL              | 40                         | 80E-TNT         | 22, 35, 49, 62, 76               | 760           | 725                | 2.5                     | WSW            |
|                    |              | SLL              |                            | 7525-1-1M       | 2, 96                            |               | 690                |                         |                |
|                    |              | Water            | 45                         | 80E-TNT         | 16, 29, 42, 55, 69, 83           | 760           | 690                | 1.8–2.7                 | SSW            |
|                    |              | Water            |                            | 7525-1-1M       | 2, 96                            |               |                    |                         |                |
| G                  | 21 July 2000 | SLL              | 65                         | 80E-TNT         | 22                               | 690           | 690                | 0.9                     | NE             |
|                    |              | SLL              |                            | 7525-1-1M       | 2, 42                            |               | 690                |                         |                |
|                    |              | Water            | 40                         | 80E-TNT         | 22                               | 790           | 760                | 0.6–1.4                 | NE–E           |
|                    |              | Water            |                            | 7525-1-1M       | 2, 42                            |               | 690                |                         |                |

<sup>†</sup>Events C and J applied only to soybean. Events D and E applied only to corn. SLL and water applied simultaneously for events A, B, and C.

<sup>‡</sup>Soybean start with row #1 and end with row #48. Corn starts with row #49 and ends with row #96. Row #(-5) is 5 rows outside row #1

<sup>§</sup>Wind data was collected from the weather station on the research farm as provided by the State Climate Office of North Carolina at NCSU.

\*Data lost or questionable.

## RESULTS AND DISCUSSION

### Preliminary Sprinkler Tests

Very little change in the radial profile was noticed for the 70CW-TNT as sprinkler pressure increased from 440 to 580 kPa (Fig. 2.3). When the straightening vane was removed from the nozzle, the distribution pattern became smoother at a sprinkler pressure of 470 kPa (Fig. 2.3). A larger wetted diameter was obtained with sprinkler 80E-TNT ( $\approx 32$  m) than 70CW-TNT ( $\approx 24$  m) as indicated by the increase in radial distance (Fig. 2.4). When the spreader nozzle was removed from 80E-TNT and replaced with a plug, the radial profile was smoother (Fig. 2.4). However, there was more variability in the data for 80E-TNT without the spreader nozzle. Some of the enhanced variability may have been due to wind effect ( $0.9 - 2.7 \text{ m s}^{-1}$ ) during the test. For the other reported tests, wind movement was minimal. Based on these results, sprinkler 80E-TNT was chosen over 70CW-TNT, in part because it covered a larger distance (wetted diameter) from the sprinkler. While a stronger triangular pattern was obtained for 80E-TNT with a spreader nozzle, 80E-TNT with the plug instead of the spreader nozzle was selected because of the lower application rates (Fig. 2.4).

To provide better coverage towards both ends of the line source, a part circle impact sprinkler was needed. Set to cover 50% of a full circle, a radial profile similar to the one obtained for the 80E-TNT without the spreader nozzle was obtained for sprinkler 7525-1-1M (Fig. 2.5). The largest difference between the sprinklers was the increase in application rate close to the sprinkler and the decrease in the wetted diameter for the 7525-1-1M.

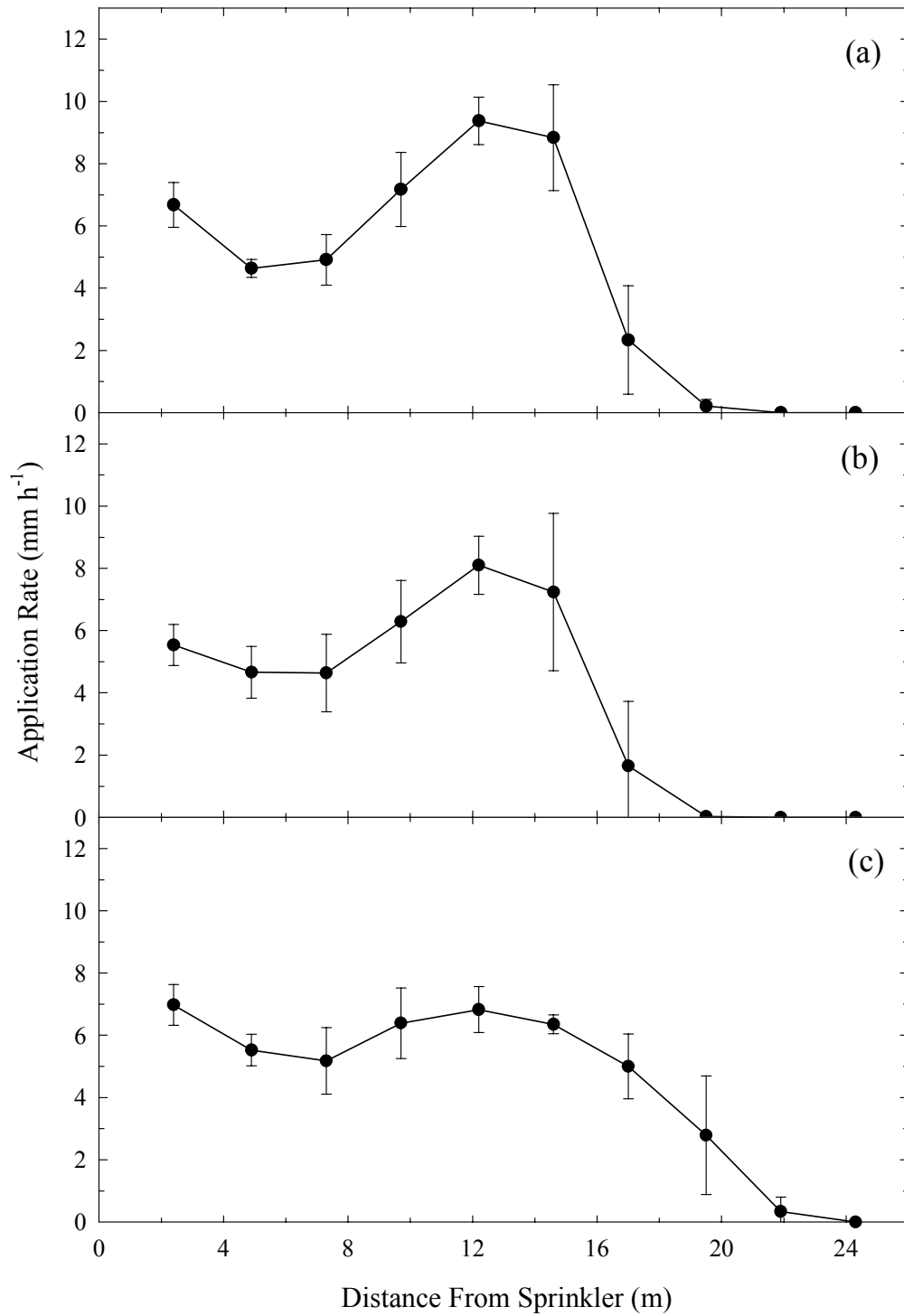


Fig. 2.3. Average radial distribution for 70CW-TNT at sprinkler pressures (a) 580 kPa, (b) 440 kPa, and (c) 470 kPa. For sprinkler test (c), the straightening vane was removed from the nozzle. Error bar represents the standard deviation of the mean from all catch cans at a given distance from the sprinkler.



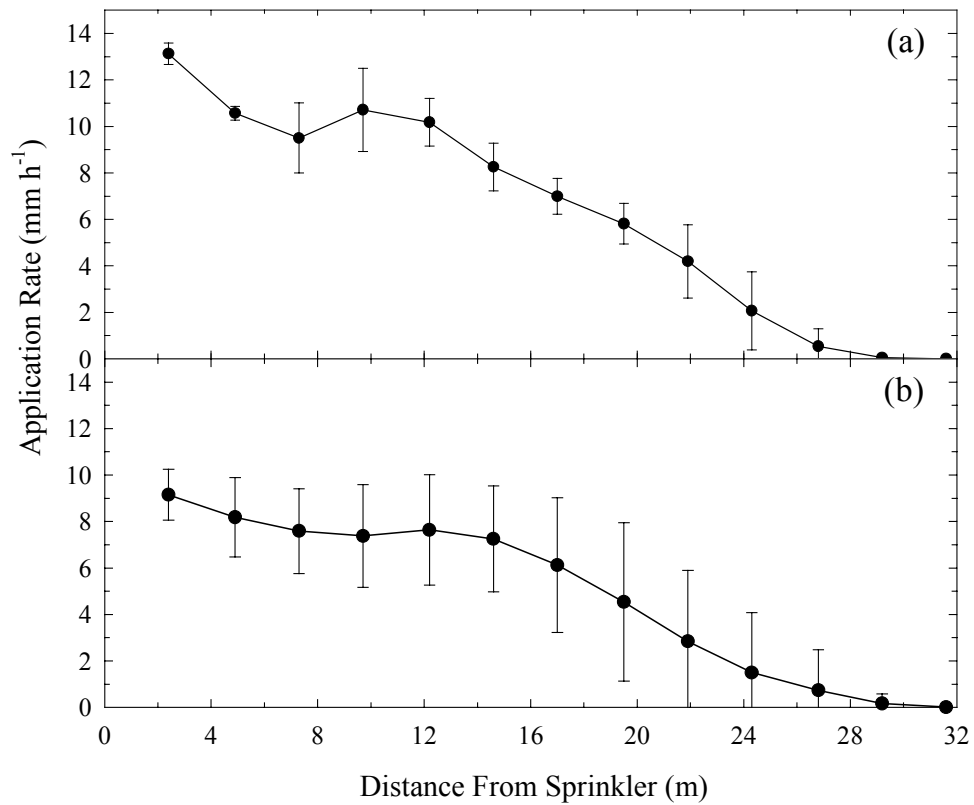


Fig. 2.4. Average radial distribution for 80E-TNT at 520 kPa with (a) spreader nozzle and (b) without spreader nozzle. Error bar represents the standard deviation of the mean from all catch cans at a given distance from the sprinkler.

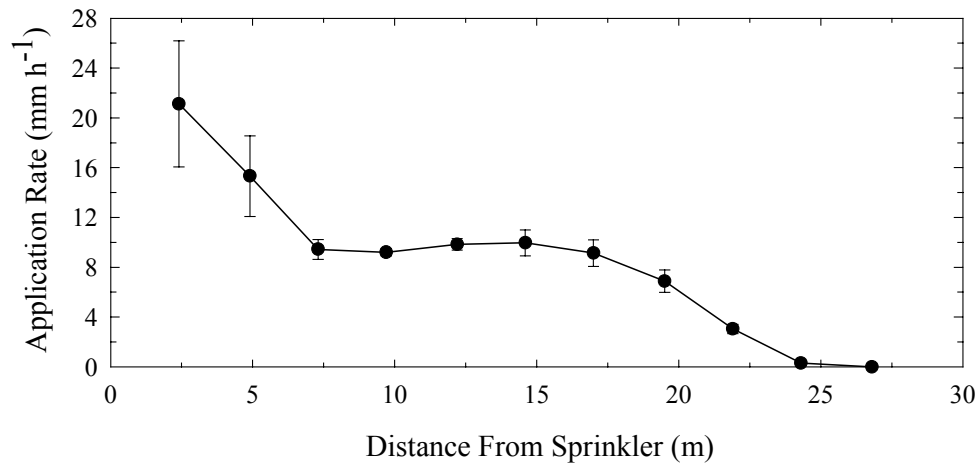


Fig. 2.5. Average radial distribution for part circle impact sprinkler (7525-1-1M) at 621 kPa. Error bar represents the standard deviation of the mean from all catch cans at a given distance from the sprinkler.

## **Irrigation Events**

A total of three irrigation events were applied in 1999 and four in 2000. The average application depths for catch cans locations in respect to line-sources were calculated for the entire field area (Fig. 2.6 and 2.7). The application depths for each experimental section (Fig. 2.2) are found at distances of 0 to 30 m for Section 1, 30 to 60 m for Section 2, and 60 to 90 m for Section 3 (Fig. 2.6 and 2.7). Fewer points are reported for Event D in 2000 (Fig. 2.7) because there were no catch can transects in line with the sprinklers. For the other irrigation events, there were at least two transects in line with the sprinklers. Irrigation Events A and B in 1999 and Events E and F in 2000 were applied to both corn and soybean. Events C in 1999 and G in 2000 were applied only to soybean. In 2000, Event D was applied to corn only.

In 1999, the average applications for Sections 1 and 3 ranged from 0 to 20 mm with decreasing distances to the line-sources for each event (Fig. 2.6). Section 2 always received higher irrigation amounts than Section 1 or 3, ranging from 15 to 30 mm on average for each irrigation event. The highest application depths within Section 2 were generally found halfway between the SLL and water line-sources (Fig. 2.6). Equal application depths were desired for Section 2 to eliminate any irrigation effect. While equal distribution was not obtained in Section 2, any irrigation effects should be minimal since the lowest application depth in Section 2 was not lower than the highest application depth recorded for Section 1 or 3. The distribution pattern for Event B shifted towards Section 3 due to wind effects ( $5.1 - 4.2 \text{ m s}^{-1}$  wind speed). Event C was applied only to the soybean.

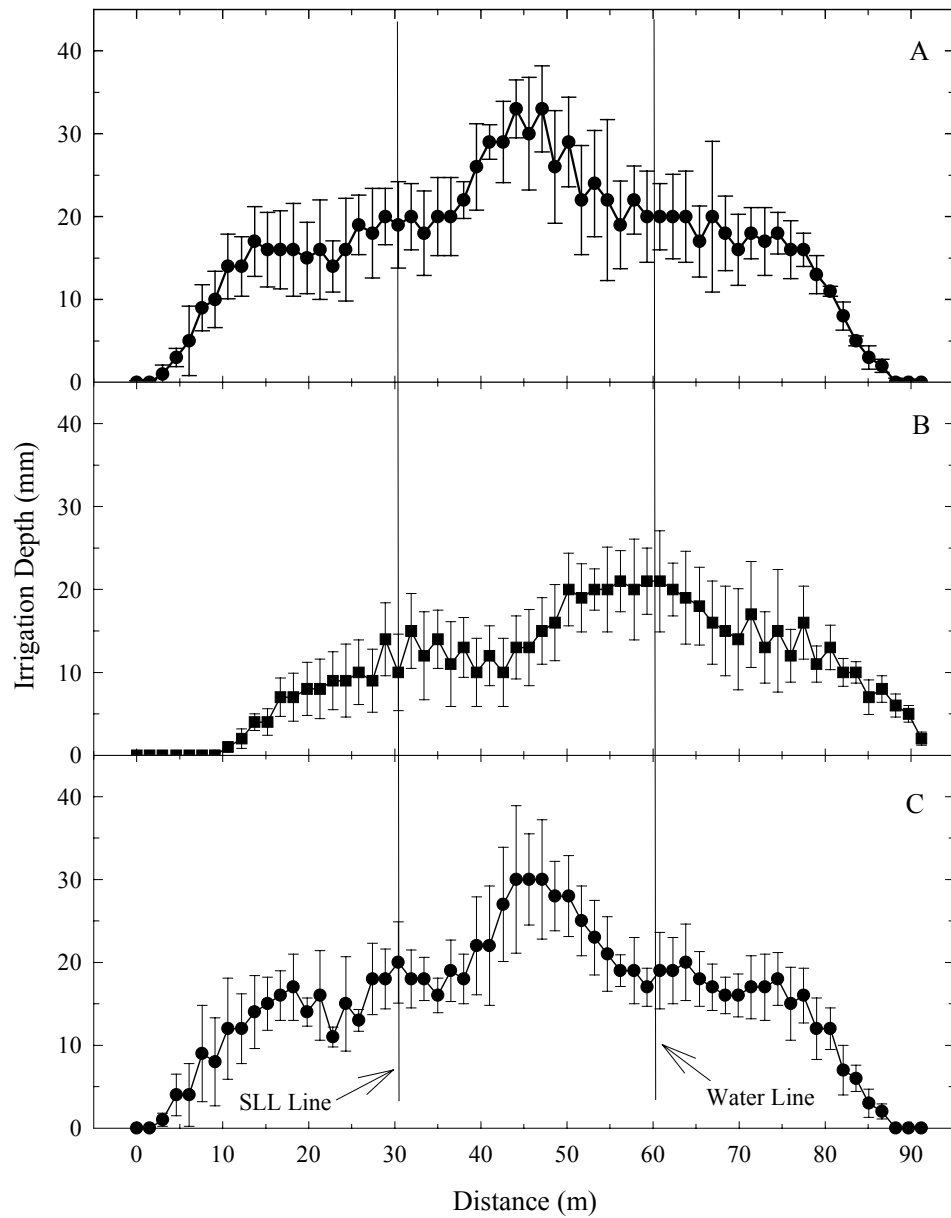


Fig. 2.6. Irrigation distribution for events A, B, and C in 1999 (see Table 2.1 for details). Error bar represents the standard deviation of the mean from all catch cans at a given distance from the sprinkler.

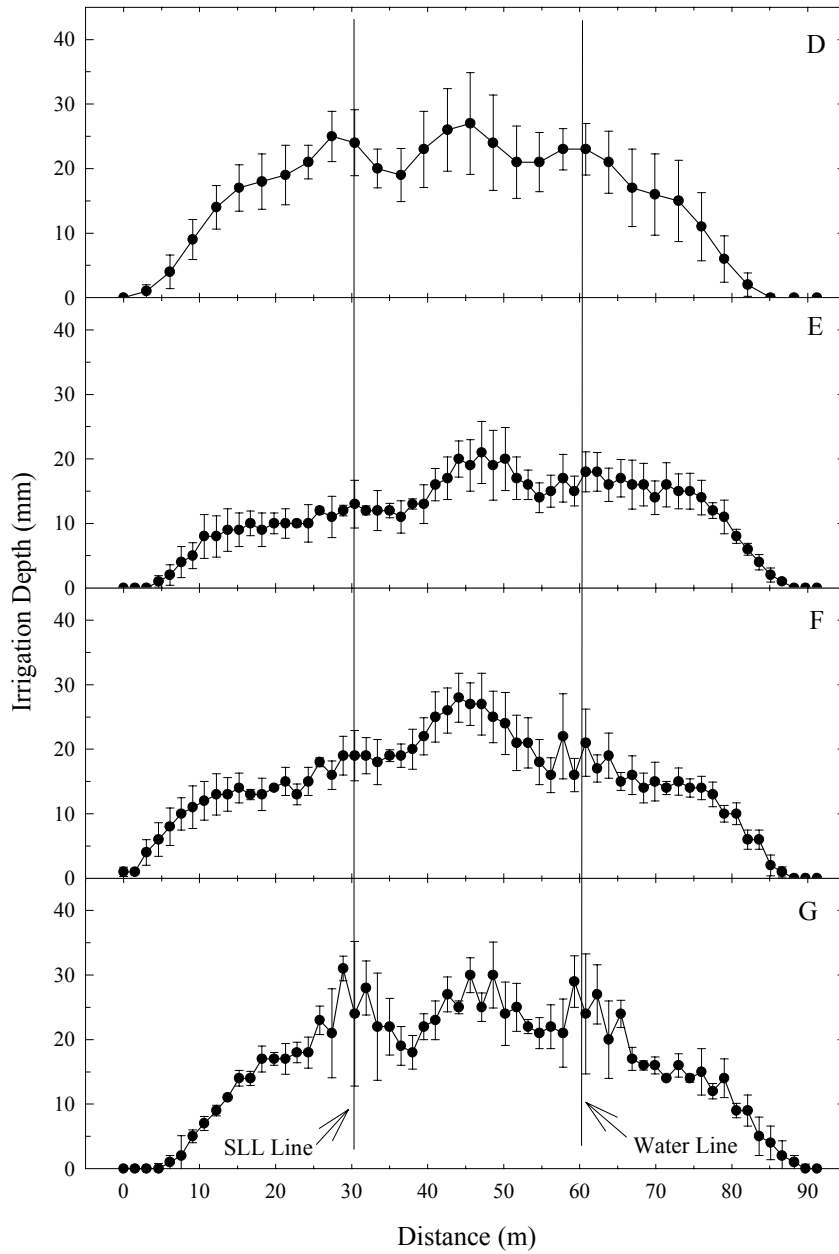


Fig. 2.7. Irrigation distribution for events D, E, F, and G in 2000 (See Table 2.2 for details about the irrigation events). Error bar represents the standard deviation of the mean from all catch cans at a given distance from the sprinkler.

Irrigation distribution patterns appear to be more uniform at a given distance from the sprinkler in 2000 (Fig. 2.7) than 1999 (Fig. 2.6). The improved uniformity resulted from closer sprinkler spacing in 2000 (Table 2.1) and the use of the part circle impact sprinklers for increased coverage toward the ends of the line-sources. The part circle impact sprinklers were not used until Event C in 1999. Events D and G were more variable than events E and F in 2000 due to fewer sprinklers used. Fewer sprinklers were used for Events D and G because only corn or soybean was irrigated respectively. Irrigation depths ranged from 0 to 20 mm in Section 1 and 3 for Events E and F (Fig. 2.7). For Section 2, average depths ranged from 12 to 28 mm with the highest depths midway between the SLL and water line-sources. When only one crop was irrigated (Events D and G), depths ranged from 20 to 30 mm and the peak between the line-sources was less distinct (Fig. 2.7). Average irrigation depths for Sections 1 and 3 ranged from 0 to 30 mm for Events D and G.

Generated maps were plotted for Event F (Fig. 2.8) comparing actual data versus theoretical data. Theoretical data using the sprinkler setup and catch can locations for Event F was obtained from the program output (see Sprinkler Tests within the Materials and Methods section). The actual map was developed from the catch cans measurements for Event F. While the application depths were similar for both maps, the distribution pattern using the actual data was more irregular. The irregularity of the pattern could be due to wind effects or the slight tilting of a sprinkler.

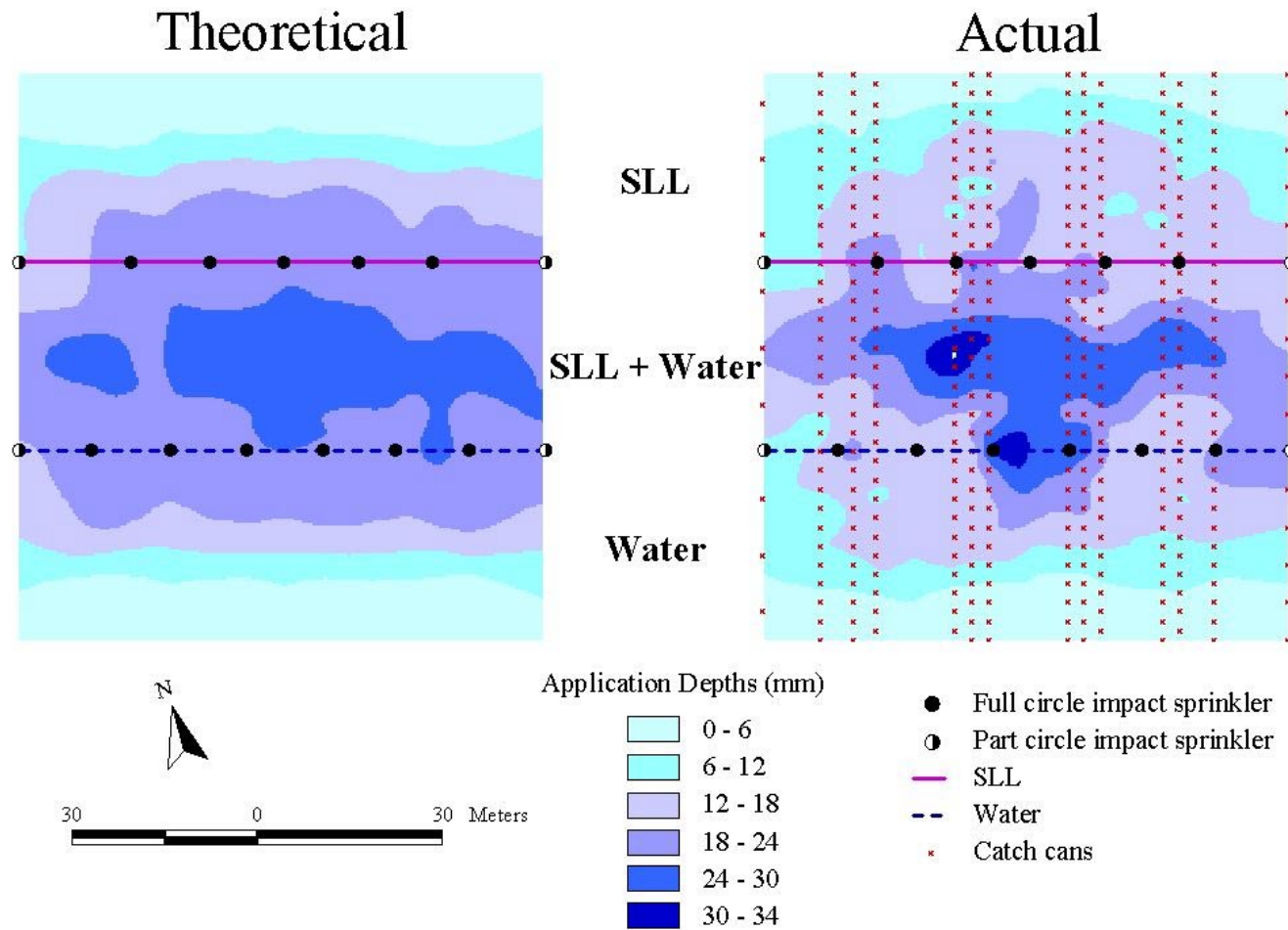


Fig. 2.8. Theoretical and actual distribution of combined water and SLL applications for Event F.

### **Estimated Nitrogen Applied**

Ammonia volatilization losses were calculated as the difference in total N concentrations of the pumped SLL and that of the SLL in the catch cans (Table 2.3). The amount of N applied from SLL was assumed to be the N content of the catch cans after irrigation as calculated by multiplying the average catch can N concentration by the SLL volume collected. Note that this calculation gives only an estimate of the total N applied because it does not include any further N losses that occur after irrigation. Less than 5 kg N ha<sup>-1</sup> each year was added with the irrigation water itself.

The amount of N applied for all transects was calculated for all SLL irrigation events (Fig. 2.9 and 2.10). The amount of applied N varied among the irrigation events due to changes in amounts of SLL applied. Also, the N concentration of the SLL dropped as the growing season progressed (Table 2.2). Variability in N applied was greater in 1999 than 2000 possibly because of the wider sprinkler spacings used in 1999. Due to windy conditions (4.2 – 5.1 m s<sup>-1</sup>) during Event B, the SLL application pattern shifted towards Section 2 by about 10 m (Fig. 2.9). This shift was also reflected with the irrigation depths (Fig. 2.6). When both crops were irrigated in 2000 (Events E and F, Fig. 2.10), N application rates were relatively constant for the first 15 m to either side of the SLL line-source. Therefore, half of Section 1 and 2 received about the same amount of N for those two events thus decreasing the number of different variable rates obtained. The N distribution map of applied SLL for Event F (Fig. 2.11) shows that N rates mainly ranged between 75 to 100 kg N ha<sup>-1</sup> within 15 m to each side of the SLL line. Events D and G showed a better triangular pattern for increases in N applied as distance from the sprinkler decreases (Fig. 2.10).

Table 2.3. Estimated ammonia volatilization losses from sprinkler irrigation of SLL.

| Event <sup>†</sup> | Start Time | Nitrogen Concentration          |                         | Estimated NH <sub>3</sub> Loss | Sprinkler Pressure | Air Temperature <sup>§</sup><br>(Initial – Final) | Relative Humidity <sup>§</sup><br>(Initial – Final) |
|--------------------|------------|---------------------------------|-------------------------|--------------------------------|--------------------|---|---|
|                    |            | Lagoon                          | Catch cans <sup>‡</sup> |                                |                    |   |   |
|                    |            | -----mg N L <sup>-1</sup> ----- |                         | %                              | kPa                | °C  | %   |
| A                  | 7:00 a.m.  | 554                             | 510                     | 8.0                            |                    | 22 – 27   | 96 - 79   |
| B                  | 8:45 a.m.  | 464                             | 437                     | 6.0                            | 760                | 21 – 23   | 86 - 78   |
| C                  | 7:20 a.m.  | 407                             | 368                     | 9.7                            | 690                | 24 – 31   | 100 - 84  |
| D                  | 8:00 a.m.  | 566                             | 527                     | 6.8                            | 690                | 23 – 27   | 70 - 56   |
| E                  | 8:10 a.m.  | 552                             | 432                     | 21.8                           | 620                | 28 – 32   | 68 - 52   |
| F                  | 8:15 a.m.  | 508                             | 442                     | 13.0                           | 725                | 24 – 27   | 72 - 66   |
| G                  | 6:50 a.m.  | 383                             | 336                     | 12.2                           | 690                | 21 – 22   | 91 - 86   |

<sup>†</sup>Events A, B and C occurred in 1999 and the rest in 2000. See Table 2.1 for more information.

<sup>‡</sup>Average concentration from random sampled catch cans.

<sup>§</sup>Information collected from the weather station on the research farm as provided by the State Climate Office of North Carolina at NCSU.



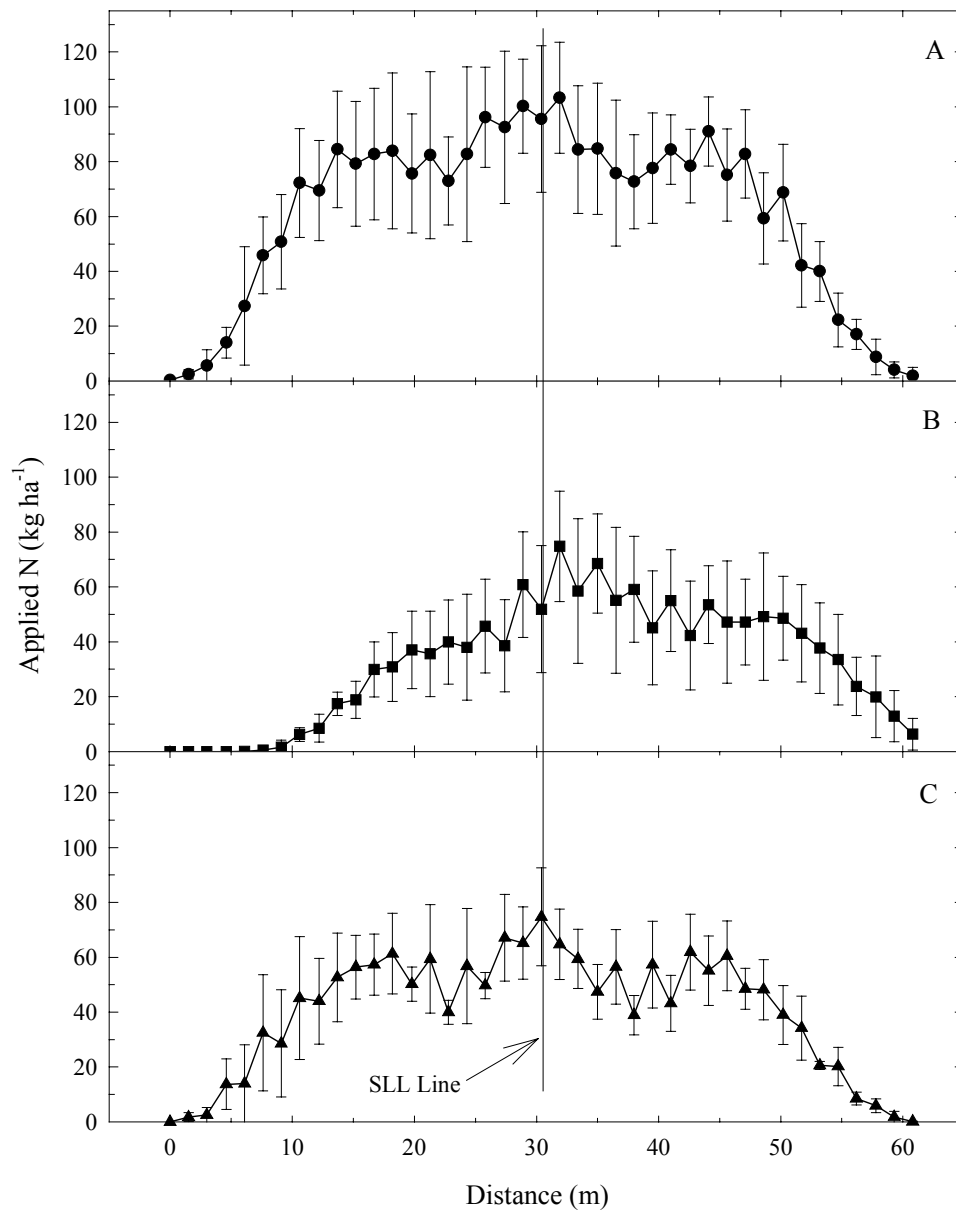


Fig. 2.9. Average N applied from SLL for all transects for irrigation events A, B, and C in 1999. Error bar represents the standard deviation of the mean from all catch cans at a given distance from the sprinkler.

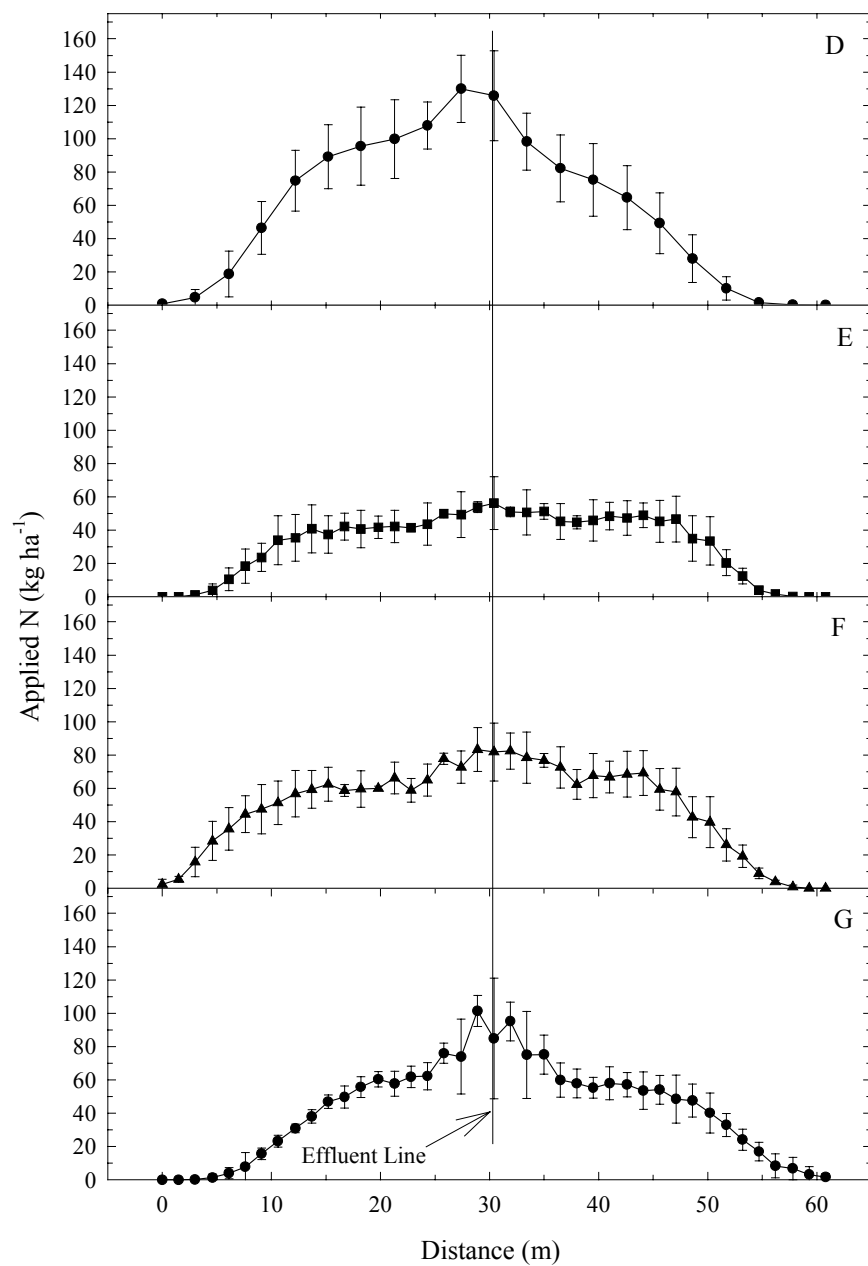


Fig. 2.10. Average N applied from SLL for all transects for irrigation events D, E, F, and G in 2000. Error bar represents the standard deviation of the mean from all catch cans at a given distance from the sprinkler.

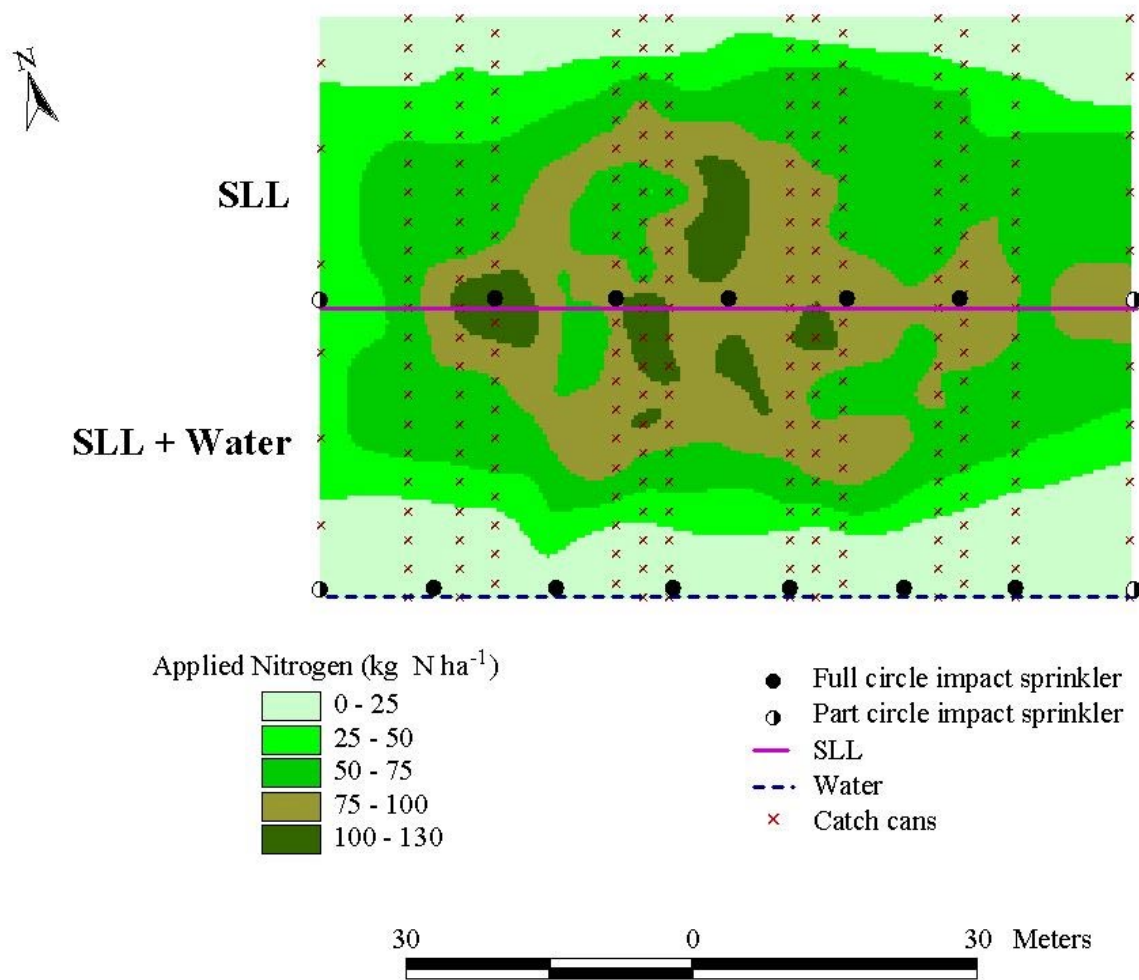


Fig. 2.11. Estimated N applied from SLL during irrigation Event F.

## CONCLUSIONS

The line-source technique was effective in delivering decreasing application rates as the distance from the sprinkler increased. Better uniformity among catch can amounts at a given distance from the sprinkler was obtained when sprinkler spacing was about 25% of the wetted diameter than when a wider spacing was used. Application uniformity decreased when fewer sprinklers were used and a smaller area irrigated to apply N to either corn or soybean only. When fewer sprinklers were used to irrigate a smaller section of the field, the decrease in N rate with increasing distance from the SLL line-source exhibited more of a triangular pattern. When both crops were irrigated in 2000, N rates from the irrigated SLL were constant for  $\approx 15$  m to either side of the SLL line.

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## CHAPTER 3

### NITROGEN EFFICIENCY OF ANAEROBIC SWINE LAGOON LIQUID APPLIED BY IRRIGATION TO FIELD CROPS

#### ABSTRACT

Anaerobic swine (*Sus scrofa domestica*) lagoon liquid is commonly applied by irrigation to hay fields or pastures as a means of waste disposal and treatment. However, little data is available concerning the irrigation of grain crops with swine lagoon liquid (SLL). During 1999 and 2000, research was conducted in the Coastal Plain of North Carolina to determine the efficiency of N removal by corn (*Zea mays* L.) and soybean (*Glycine max* Merrill) from applied SLL in comparison to  $\text{NH}_4\text{NO}_3$ . A continuously variable N application rate from SLL, ranging from 0 to  $200 \text{ kg ha}^{-1}$ , was achieved using the line-source sprinkler irrigation technique. A nonnodulating soybean isoline was added to the experiment in 2000 to assist in the evaluation of SLL applications to nodulating soybean. Corn response to SLL and  $\text{NH}_4\text{NO}_3$  was measured by chlorophyll readings, ear leaf N contents, grain yields, and grain N removed. Soybean response to SLL and  $\text{NH}_4\text{NO}_3$  was measured by grain yields and grain N removed. When only SLL was applied, corn yields increased with SLL additions in 1999 and 2000 when only SLL was applied. However, when variable N rates of SLL were applied with equal water amounts in 1999, no increase in corn yields was noticed for SLL additions. An increase in yield was noticed for the nodulating soybean following additions of SLL only in 1999. The nonnodulating soybean yields increased with increasing amounts of SLL. In 1999, grain N recovery was affected more by the amount of liquid applied

than the amount of N supplied by SLL. In 1999, N recoveries in grain were estimated to be <15% for both corn and soybean at 168 kg N ha<sup>-1</sup> from either SLL or NH<sub>4</sub>NO<sub>3</sub>. In 2000 at the 168 kg ha<sup>-1</sup> N rate, recovery of SLL-applied N in grain was 28% for corn, 25% for nonnodulating soybean, and 39% for nodulating soybean. Respective recoveries from NH<sub>4</sub>NO<sub>3</sub> applied at 168 kg N ha<sup>-1</sup> were 45, 31, and 56%. It appears that nodulating soybean may recover more of the applied N from either SLL or NH<sub>4</sub>NO<sub>3</sub> than does corn. Based on yield and grain N removed, about 55% of the N in the SLL was available for plant utilization when volatilization losses during irrigation were around 22%.



## INTRODUCTION

Application of SLL onto agronomic crops by irrigation is the most common means of disposal because of the essential plant nutrients present. Bermudagrass (*Cynodon dactylon*), used either as hay or pasture, is the most common crop used as the receiver of the SLL. The high nutrient requirement, ease of management, and length of uptake period (from April to September) encourage the use of bermudagrass as a receiver crop for SLL (NCCES, 1990; Burns et al. 1990). However, when bermudagrass is grazed by cattle, the amount of nutrients removed is lower than when it is used for hay production. Also, due to the low economic value of bermudagrass hay within a region, hay bales may be left rotting along the field edge where the nutrients are ultimately returned back to the environment. Therefore grain crops such as corn and soybean may be a better receiver of SLL since the harvested grain is removed from the field and sold off the farm.

In North Carolina, land application of SLL is based on the amount of N supplied to a growing crop. Plant-available nitrogen (PAN) is a term that refers to the amount of N from an organic waste, such as SLL, that will potentially be available to the plant. The purpose for determining PAN is to estimate the amount of an organic waste required to reach an equivalent amount of inorganic fertilizer N. For SLL applications in North Carolina, N availability coefficients based on collection and application methods (Table 3.1) are used by the North Carolina Department of Agriculture and the North Carolina Cooperative Extension Service to determine PAN (NCCES, 1990; Westerman et al., 1995). Plant-available N is calculated by multiplying the N availability coefficient by the N concentration from the lagoon liquid. An availability

coefficient of 50% is used for SLL to be applied by irrigation, meaning that half of the total applied N will become available for plant uptake during the growing season. For environmental and economic reasons, this coefficient must be determined accurately. Based on these concerns and the need for information regarding application of SLL to grain crops, research was conducted to determine PAN of SLL applied to grain crops by irrigation. The objectives of this research were to (1) measure corn and soybean utilization of applied N from SLL in comparison to  $\text{NH}_4\text{NO}_3$  and (2) determine PAN from crop utilization comparisons of SLL to  $\text{NH}_4\text{NO}_3$ .

Table 3.1. First-year N availability coefficients for swine manure based on collection and application method<sup>†</sup>.

| Collection Method       | Soil                   |                            |           |            |
|-------------------------|------------------------|----------------------------|-----------|------------|
|                         | Injection <sup>‡</sup> | Incorporation <sup>§</sup> | Broadcast | Irrigation |
| Scraped paved surface   | —                      | .6                         | .4        | —          |
| Liquid manure slurry    | .8                     | .7                         | .4        | .3         |
| Anaerobic lagoon liquid | .9                     | .8                         | .4        | .5         |
| Anaerobic lagoon sludge | .6                     | .6                         | .4        | .4         |

<sup>†</sup>Obtained from Zublena et al. (1990).

<sup>‡</sup>Manure injected directly into the soil.

<sup>§</sup>Manure spread onto the soil surface and incorporated within 2 days.

## MATERIALS AND METHODS

Field research was conducted on the Upper Coastal Plain Research Station located near Rocky Mount, NC. The majority of the field, listed as P7 on the Research Station, has been classified as an Eunola loamy sand (fine loamy, siliceous, thermic, Aquic Hapludults) with 0 to 3% slopes (Kleiss et al., 1983). The soil is somewhat poorly drained such that the water table is 0.5 to 0.8 m below the ground surface during

wet periods. Based on soil samples sent to the North Carolina Department of Agriculture Agronomic Division, no additions of lime, P, or K were needed for either corn or soybean. In previous years, the field was planted in corn and SLL was applied at recommended agronomic rates of N.

Monthly rainfall amounts from the Research Station were recorded for 1999 and 2000 (Fig. 3.1). Rainfall was significantly higher during September 1999 because of hurricanes Dennis and Floyd. The field was flooded for several days immediately after hurricane Floyd.

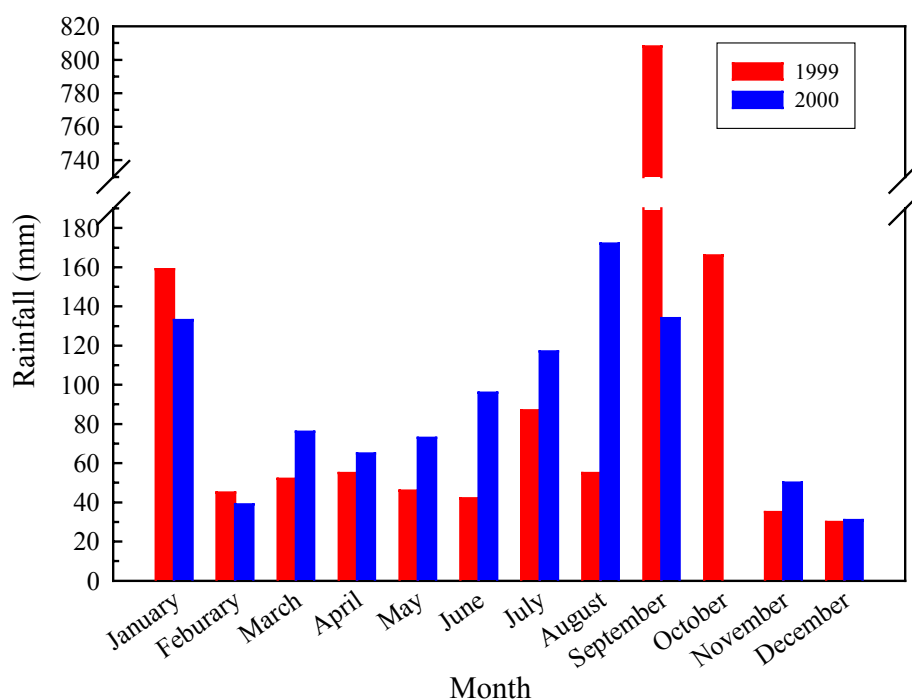


Fig. 3.1. Monthly rainfall distribution during 1999 and 2000 at the Upper Coastal Plain Research Station near Rocky Mount, NC.

## **Experimental Design and Implementation**

The experimental layout, Fig. 2.2 in Chapter 2, consisted of 48 rows of corn and 48 rows of soybean. The supply lines for the effluent and water sprinklers were laid perpendicular to the rows. Based on the maximum throw of the sprinklers, the water line was spaced 30m away from the effluent line. The rows were divided into three sections depending on the location of the supply lines for the sprinklers. Section 1 received only variable rates of SLL. Located between the SLL line and the water line, Section 2 received variable rates of SLL along with variable rates of water to balance the amount of liquid applied across the section. Section 3 consisted of randomized fertilizer treatments that received variable rates of water. Transects of catch cans were placed along the rows in conjunction with the location of the sprinklers to measure the amount of SLL and water applied. More details of the irrigation design are presented in Chapter 2.

Both corn and soybean were managed with conventional tillage practices. The crops were planted in 0.9m rows and cultivated once during the growing season. For 1999, Pioneer 3394 corn was planted on 6 April and Pioneer 95B71 soybean was planted on 24 May. In 2000, Pioneer 3394 corn was planted on 11 April and Asgrow 6101RR soybean was planted on 12 May. Also in 2000, four rows within the soybean plot were planted with a nonnodulating soybean isoline, Lee (D68-0102). The plant population for corn was about 55,000 ha<sup>-1</sup> in 1999 and 2000. For soybean, the plant population was approximately 210,000 ha<sup>-1</sup> in 1999 and 280,000 ha<sup>-1</sup> in 2000. The Research Station staff handled field preparation, planting and weed control for both years. The nonnodulating soybeans were hand weeded once during the growing season.

During 2000, deer significantly reduced the vegetative growth of the nodulating soybean within Section 3. Aboveground biomass samples from Section 3 and Section 1 (no deer damage) at 6 and 8 weeks after planting were collected (1 m of row), dried, and weighed. The reduction in vegetation was 63 and 60% at 6 and 8 weeks respectively.

### **Nitrogen Applications**

Section 1 and 2 received N from irrigation with SLL. Applied N was calculated for each irrigation event by measuring total Kjeldahl N from SLL samples and accounting for  $\text{NH}_3$  volatilization losses during irrigation. Details for N analysis are given in Chapter 2.

Section 3 consisted of randomized  $\text{NH}_4\text{NO}_3$  treatments of 0, 56, 112, 168, and 224 kg N  $\text{ha}^{-1}$  with continuously variable water amounts. Each treatment consisted of 9 rows 36 m in length, except for the nonnodulating soybean in 2000. The nonnodulating soybean fertilizer plots were adjacent to the soybean plot in Section 3 (see Fig. 2.2) and received no water through irrigation. Plot size for the nonnodulating soybean randomized fertilizer treatments was 4 rows 4.6 m long. In 1999,  $\text{NH}_4\text{NO}_3$  was broadcasted in two split applications using a drop spreader one month after corn planting (28 May) and one month later (23 June). In 2000, the  $\text{NH}_4\text{NO}_3$  was banded by hand with the first application to corn and soybean being one month after corn planting (16 May). The second application was about one week later (26 May) for the corn and one month later (27 June) for the soybean.

## **Crop Response**

Crop responses to SLL were determined by collecting samples at each catch can location ( $\approx 3$  m apart) from 3 transects. Catch cans were used to measure the amount of SLL and water applied (see Chapter 2 for details). For crop response to  $\text{NH}_4\text{NO}_3$ , measurements were taken at each catch can location along a transect within each fertilizer N rate.

The ear leaf from the primary ear was taken at silking from three plants and combined for N analysis. During sampling, the corn ear leaves were checked for leaf color intensity using a hand-held chlorophyll meter (SPAD-502 Chlorophyll Meter, Minolta Camera Co., Ltd., Japan). Based on the principle of measurement developed by Inada (1963), the chlorophyll meter measures leaf color intensity by measuring the difference in light attenuation between wavelengths 430 and 750 nm. The difference in light attenuation is converted into a SPAD (Soil Plant Analysis Development) unit ranging from 0 to 80 by the meter. The number generated can then be correlated with the N status of a crop (Wood et al., 1992).

After analysis with the chlorophyll meter, the leaves were dried at 60°C and ground in a Wiley mill to pass a 1-mm stainless steel screen. The tissue samples were analyzed for N by the Service Analytical Laboratory of the Soil Science Department at NCSU using the total combustion technique with a Perkin-Elmer (PE 2400CHN) elemental analyzer.

Corn yield was determined by hand harvesting the ears from 10 plants in rows on both sides of a catch can location (total of 20 plants). After the ears had been dried and weighed, random ears were hand shelled to determine the ratio of grain to cob

weight. Grain samples were oven dried to determine moisture content. Corn grain yield is reported at 15.5% moisture.

Soybean yields were determined by hand harvesting 2.3 m of row on each side of every catch can from 3 transects. A portable thresher was used to separate the grain from the pods. The grain was weighed and subsamples dried to determine moisture content. Final yield measurements were adjusted to 13% moisture.

Random grain samples from the crops were oven dried at approximately 60°C and ground in a rock grinder. Grain N concentrations were measured by the Soil Science Analytical Services Laboratory as previously described. Total grain N removal was calculated by multiplying the seed N concentration by the grain yield at 0% moisture.

### **Statistical Analysis**

Statistical analysis of data obtained from a line-source sprinkler experiment is complex due to the systematic arrangement of the irrigation levels that imposes a spatial relationship between irrigation levels. For experiments in which the data points are spatially related, repeated measures analysis has been recommended to test for treatment effects (Fernandez, 1991).

The PROC MIXED procedure in SAS (1998) was used to evaluate crop responses to N and water variables. Year and sections were treated as fixed effects and transects within the sections were treated as random effects. The REPEATED statement was used to specify the covariance structure for observations taken on the same transect. An exponential covariance function was assumed to describe the

covariance as a function of distance along the transect between measurements. The amount of N applied was used as a linear predictor for all sections. For Sections 2 and 3, application depth from the irrigation events was included as a second linear predictor. Section 1 could not be tested for irrigation effects since the amount of applied N was correlated to application depth. The slopes and intercepts for the equations relating crop response to applied N were generated by requesting the solution for fixed-effects parameters in the MODEL statement. Because there was more than one random effect, the coefficient of determination ( $r^2$ ) was not obtainable using the MIXED procedure. Significant differences between sections were determined by adding ESTIMATE statements.

## **RESULTS AND DISCUSSION**

Generally, crop responses to applied N were higher in 2000 as compared to 1999 partially because of better rainfall distribution during the growing season (Fig. 3.1). The rainfall during September 1999 was higher than average because of hurricanes Dennis and Floyd. While the field was flooded for several days after hurricane Floyd, grain yields did not appear to be negatively affected. The corn had been harvested prior to the hurricanes. The soybean, while not fully matured, had grain yields similar to other soybean grown on the farm in fields not flooded.

In 2000, deer grazed the soybean in Section 3. Two months after planting, a 60% reduction in soybean biomass between Section 1 and Section 3 was measured. While there was a significant reduction in soybean biomass 2 months after planting, grain yield did not appear to be negatively impacted by the grazing.



## Corn Nitrogen Uptake

During the growing season, corn response to added N was measured by chlorophyll measurements and leaf tissue N concentration at early silking. Chlorophyll measurements are based on differences in light wavelength attenuation as measured by a hand-held chlorophyll meter. As the amount of chlorophyll increases, leaf greenness also increases which is interpreted as a SPAD unit by the chlorophyll meter. Therefore as leaf color intensifies, a higher SPAD unit is obtained. Previous research suggests that a SPAD unit reading in the range of 50 to 53 at the early reproductive stage (R1) is needed for no yield loss due to N deficiency (Sunderman et al., 1997; Piekielek et al., 1995; Schepers et al., 1992; Wood et al., 1992). However, SPAD units can vary based on factors other than N fertilization such as growth stage and hybrid differences.

For Section 1, SPAD readings increased significantly from about 45 to 60 units as applied N increased from 0 to 200 kg ha<sup>-1</sup> in 1999 and 2000 (Fig. 3.2). SPAD readings reached a maximum of 60 units when 200 kg N ha<sup>-1</sup> was applied in 2000 (Fig. 3.2). Since the highest N application rate in 1999 was 200 kg N ha<sup>-1</sup> as compared to ≈300 kg N ha<sup>-1</sup> in 2000, SPAD readings did not plateau at 60 units. Based on SPAD unit readings <50, it appears that N may have been limiting in Section 1 (Fig. 3.2) when applied N was <75 kg ha<sup>-1</sup> in 1999 and 50 kg ha<sup>-1</sup> in 2000. However, it is difficult to draw any conclusions from only these results since application depth increased from 0 to 60 mm as applied N increased from 0 to ≈300 kg ha<sup>-1</sup>. Since all SPAD readings were >50 units in Section 2 (Fig. 3.3), where application depths were similar as applied N increased from 0 to 250 kg ha<sup>-1</sup>, SPAD readings in Section 1 were likely affected by the amount of water applied in 1999 and 2000.

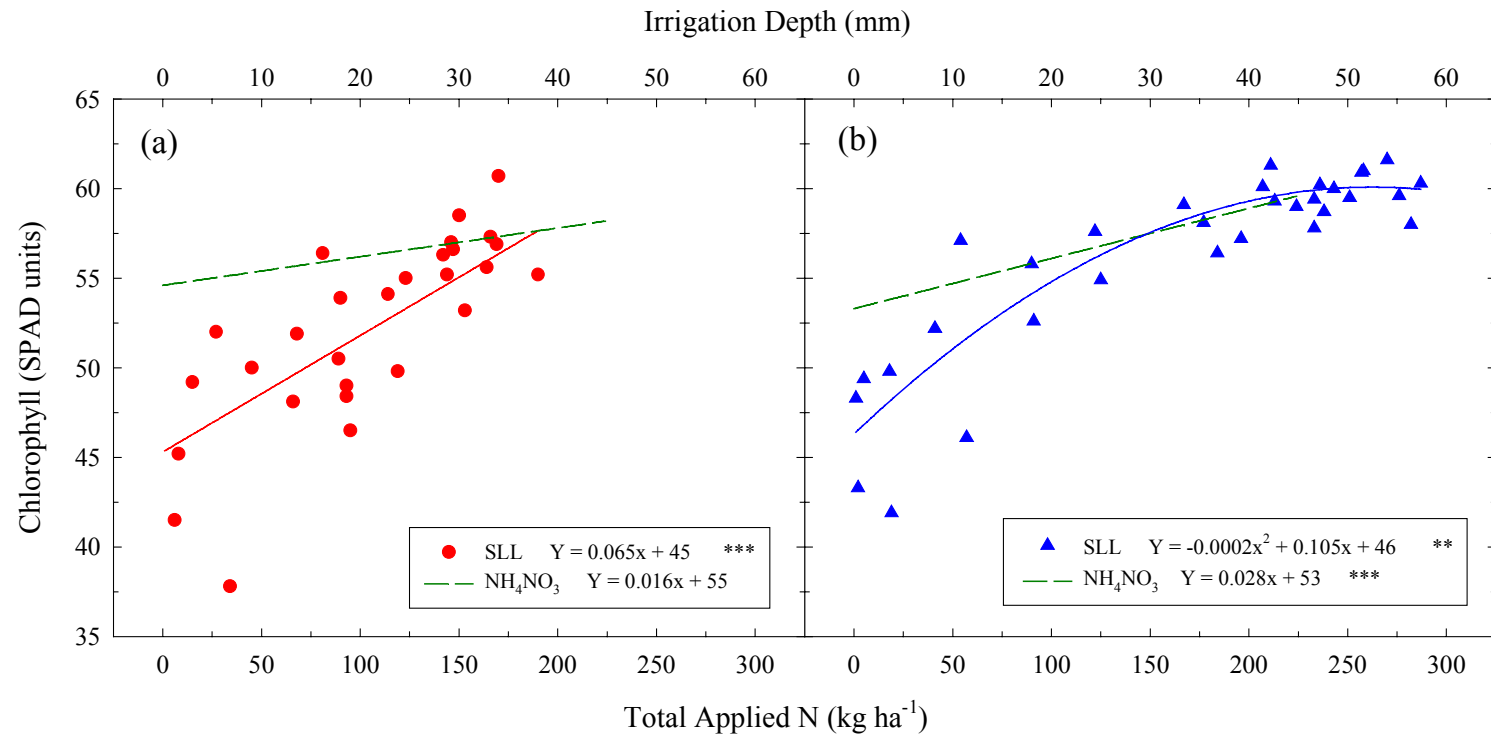


Fig. 3.2. Chlorophyll meter readings of the corn ear leaf in (a) 1999 and (b) 2000 as influenced by SLL additions in Section 1 and fertilizer applications in Section 3. Irrigation depth pertains only to SLL applications. \*\*, \*\*\* indicate slopes significant at the 0.01 and 0.001 probability levels respectively.

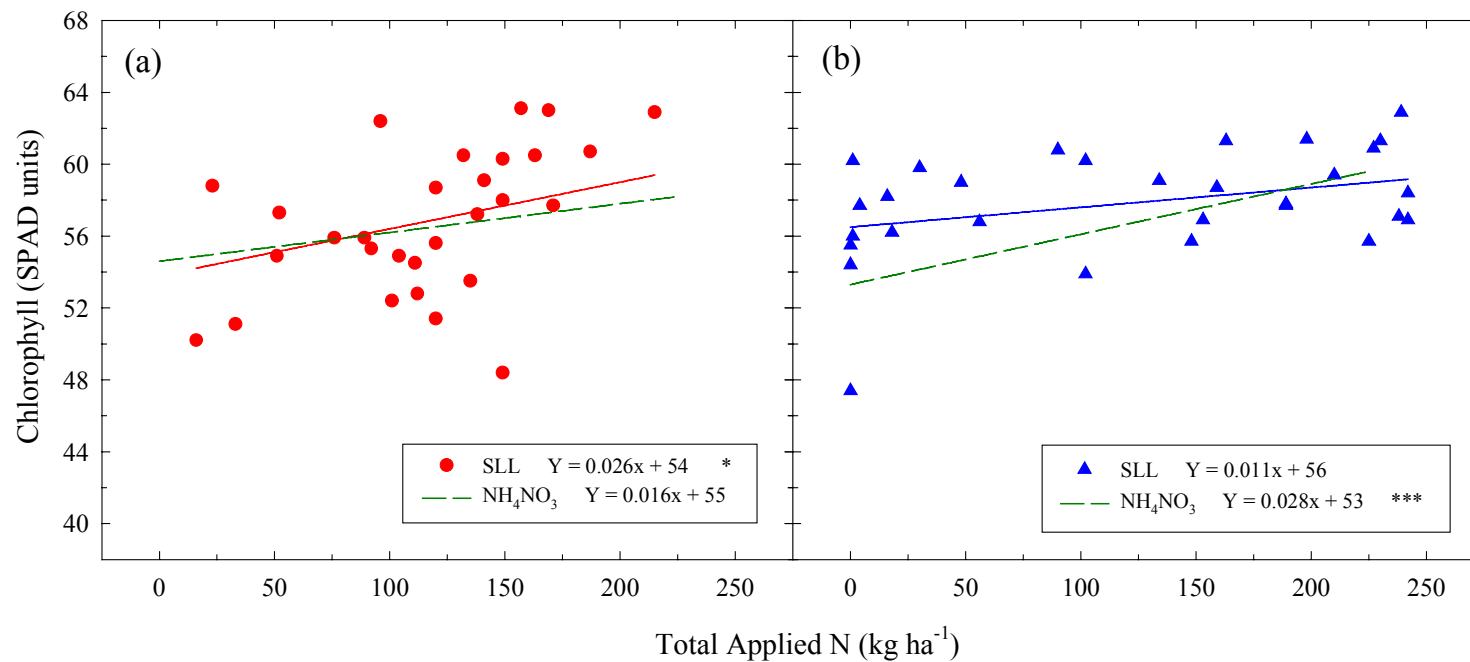


Fig. 3.3. Chlorophyll meter readings of the corn ear leaf in (a) 1999 and (b) 2000 as influenced by SLL additions in Section 2 and fertilizer applications in Section 3. \*, \*\*\* indicate slopes significant at the 0.05 and 0.001 probability levels respectively.

Generally, N additions from SLL had little effect on leaf SPAD readings in Section 2 for 1999 and 2000 (Fig. 3.3). While a significant ( $p < 0.05$ ) increase in leaf SPAD readings was noticed in 1999 from SLL additions, the data were more variable than in 2000. Because of the variability, differences between years for SPAD unit increases from SLL additions were not significant. Irrigation depth had no effect on leaf SPAD readings in Section 2.

The increase in leaf SPAD readings from additions of fertilizer N (Fig. 3.4) reflects different  $\text{NH}_4\text{NO}_3$  rates that received variable water applications ranging from 0 to 60 mm. In 2000, the increase in leaf SPAD readings with increases in  $\text{NH}_4\text{NO}_3$  was not affected by irrigation depth. In 1999, leaf SPAD readings were affected by irrigation depth. For simplicity, the  $\text{NH}_4\text{NO}_3$  curve for 1999 represents all the data instead of specific fertilizer curves for different irrigation depths. There was no significant ( $p < 0.05$ ) difference between the fertilizer additions (Section 3) and the SLL additions in Section 2 for 1999 or 2000 (Fig. 3.3).

Corn ear leaf N concentrations increased significantly with additions of SLL or  $\text{NH}_4\text{NO}_3$  both years (Fig. 3.5 and 3.6) except for Section 1 in 1999 (Fig. 3.5). In most cases, ear leaf N concentrations reached a maximum around 150 to 200 kg N ha<sup>-1</sup>. A quadratic plateau relationship was found to be significant between leaf N concentrations and N application rates of SLL in Section 1 for both years (Fig. 3.5). For Section 2 in 1999 and 2000 (Fig. 3.6), the increase in leaf N from additions of SLL was best described by a positive linear relationship. The difference between response curves in Sections 1 and 2 was probably caused by the increases in irrigation depths used to apply more N in Section 1. Application depths were similar for all N rates in Section 2.

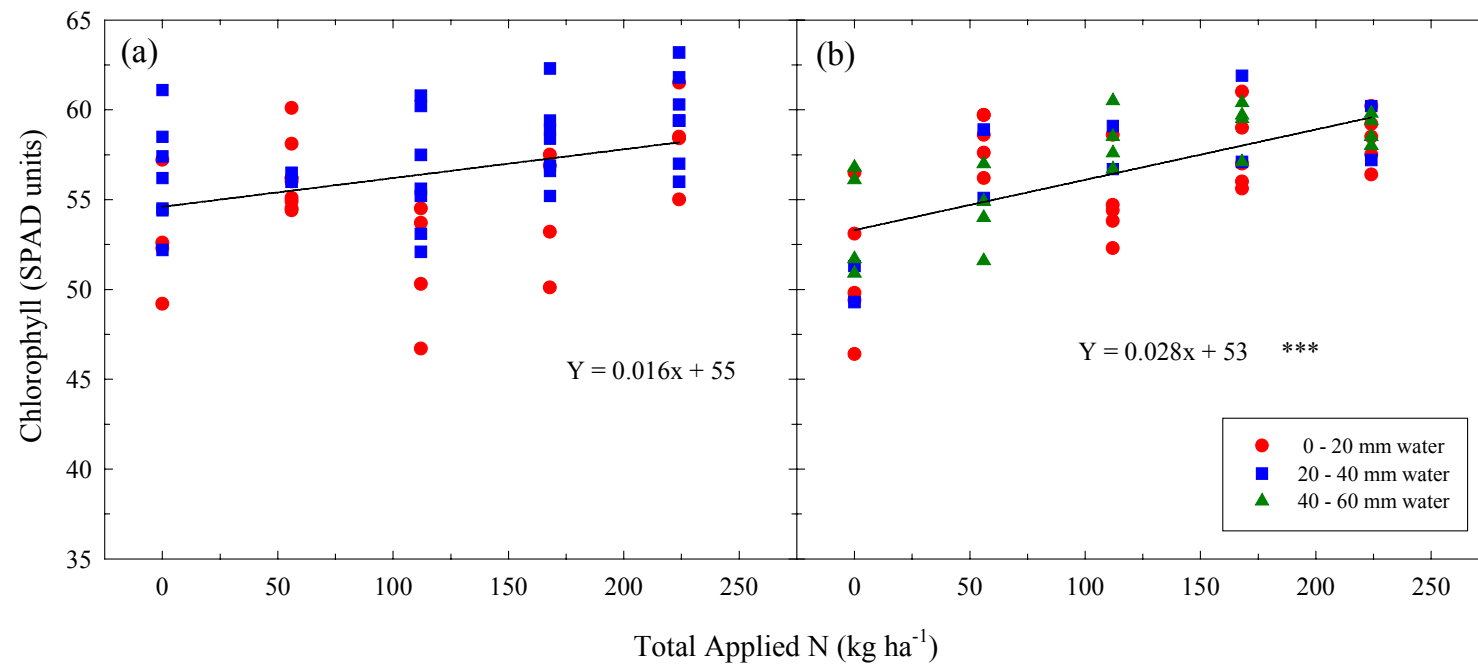


Fig. 3.4. Chlorophyll meter readings of the corn ear leaf in (a) 1999 and (b) 2000 as influenced by  $\text{NH}_4\text{NO}_3$  additions and increases in water irrigation depths in Section 3. \*\*\* indicates slope significant at 0.001 probability level.

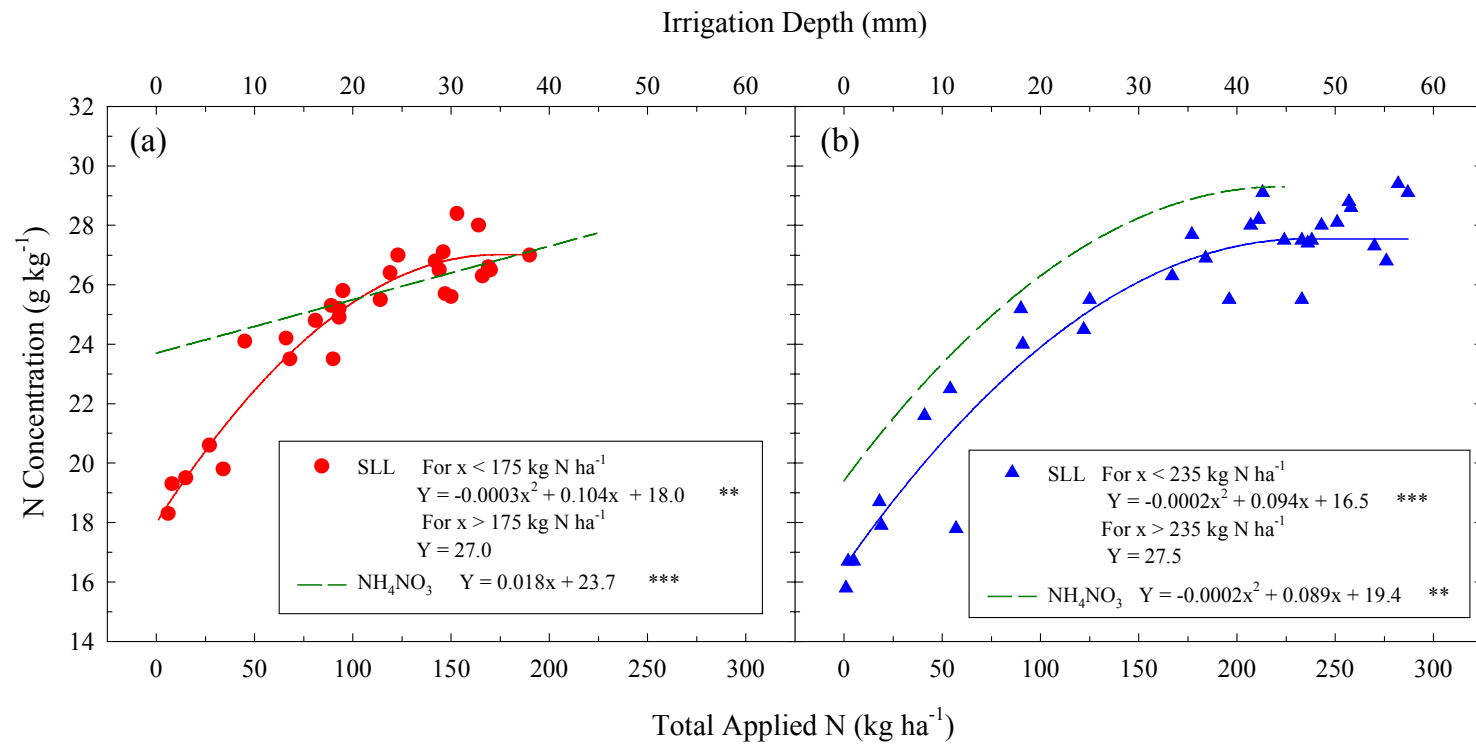


Fig. 3.5. Corn ear leaf N concentrations in (a) 1999 and (b) 2000 as influenced by SLL additions in Section 1 and fertilizer applications in Section 3. Irrigation depth pertains only to SLL applications.  
 \*\*, \*\*\* indicate slopes significant at the 0.01 and 0.001 probability levels respectively.

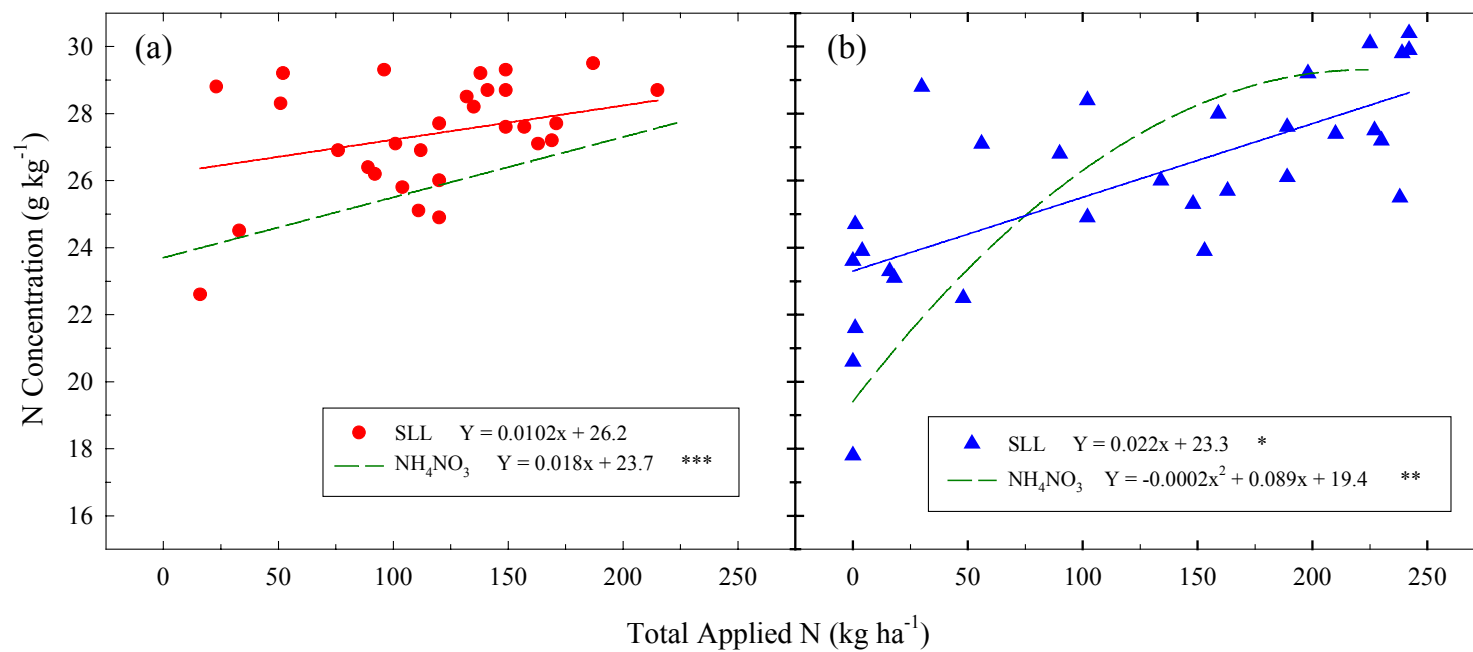


Fig. 3.6. Corn ear leaf N concentrations in (a) 1999 and (b) 2000 as influenced by SLL additions in Section 2 and fertilizer applications in Section 3. \*, \*\*, \*\*\* indicate slopes significant at 0.05, 0.01, and 0.001 probability levels respectively.

For Section 3, additions of  $\text{NH}_4\text{NO}_3$  significantly increased tissue N concentrations in 1999 and 2000 (Fig. 3.7). Due to the variable irrigation depths in Section 3, leaf N was significantly affected by the amount of water applied in 1999. However, in 2000, increases in application depths did not necessarily result in higher leaf N concentrations within a specific N rate (Fig. 3.7). Therefore, irrigation depths did not significantly influence leaf N concentrations for Section 3 in 2000. Also, the intercepts for leaf N relationship to  $\text{NH}_4\text{NO}_3$  additions were significantly different between years (Fig. 3.7). At  $0 \text{ kg N ha}^{-1}$ , leaf N concentrations ranged from 21 to  $27 \text{ g kg}^{-1}$  in 1999 and 16 to  $22 \text{ g kg}^{-1}$  in 2000. The differences between initial leaf N concentrations suggest that residual soil N levels were higher in 1999 than 2000 in Section 3.

The difference between SLL and  $\text{NH}_4\text{NO}_3$  applications on leaf N concentrations was difficult to compare due to the response curves obtained (Fig. 3.5 and 3.6). In 2000, the change in leaf N concentrations from additions of SLL in Section 1 was similar to the  $\text{NH}_4\text{NO}_3$  response (Fig. 3.5). While a direct comparison between SLL in Section 1 and  $\text{NH}_4\text{NO}_3$  in Section 3 was not possible due to the variable application depths in Section 1, higher leaf N concentrations were obtained from the fertilizer than SLL at rates  $>175 \text{ kg N ha}^{-1}$ . At this N rate in Section 1, water deficits were not a factor since an irrigation depth  $>35 \text{ mm}$  was obtained from the applied SLL. The difference in leaf N concentrations between SLL and  $\text{NH}_4\text{NO}_3$  at  $175 \text{ kg N ha}^{-1}$  suggests that the estimated applied N from SLL was not equivalent to the same amount of inorganic fertilizer (Fig. 3.5). Nitrogen rates from SLL were based on the measured N contents from catch cans after irrigation. Therefore, applied N from SLL accounted for only N losses due to during irrigation, not losses from crop and soil surfaces after irrigation.



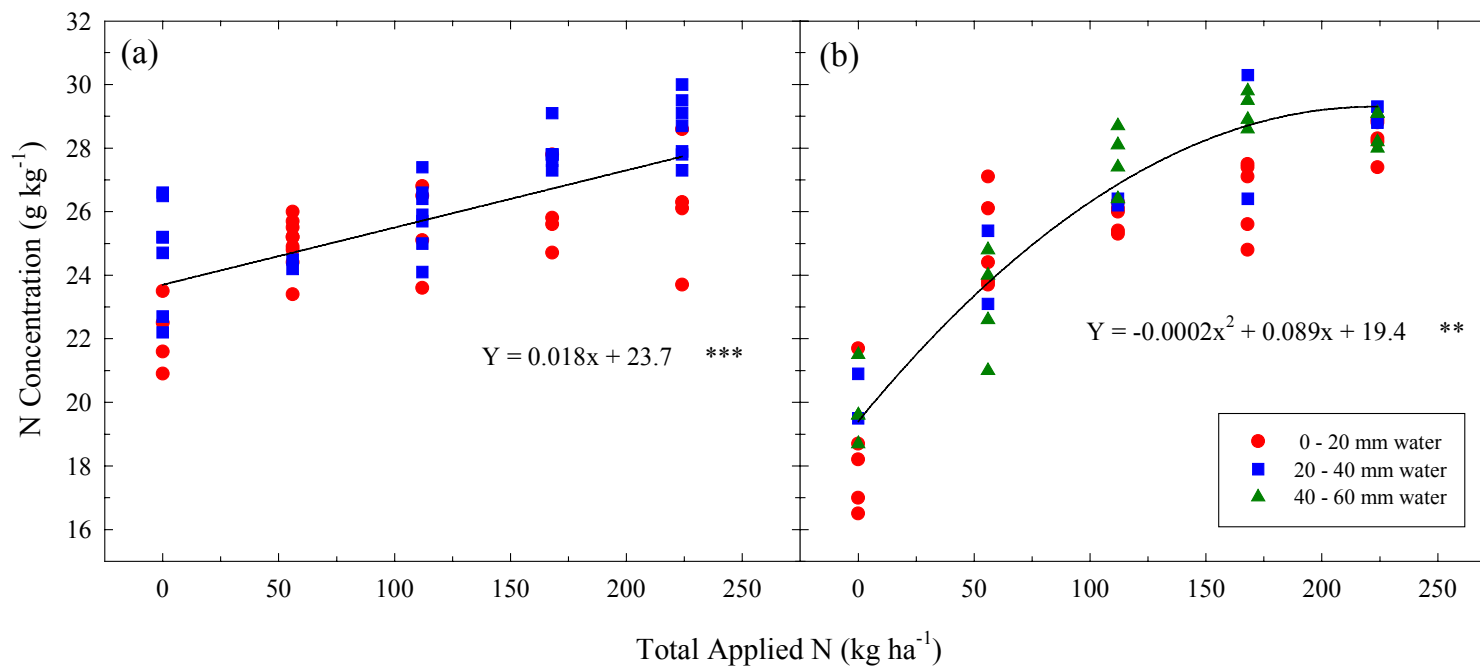


Fig. 3.7. Corn ear leaf N concentrations in (a) 1999 and (b) 2000 as influenced by  $\text{NH}_4\text{NO}_3$  additions and increases in water irrigation depths in Section 3. \*\*, \*\*\* indicate slopes significant at 0.01 and 0.001 probability levels respectively.

SPAD readings were positively correlated with N concentrations of the corn ear leaf (Fig. 3.8). Stronger correlations between SPAD readings and tissue N were found in 2000 than 1999. The sections (1, 2, and 3) also differed in the relationship between SPAD readings and tissue N. Most of the leaf N concentrations ranged from 26 to 30 g kg<sup>-1</sup> in correlation to SPAD readings of 55 to 64. Thus, suggesting a maximum level of leaf N to SPAD reading being obtained. These observations are similar to those reported by Ma and Dwyer (1997) and Wood et al. (1992) with maximum ear leaf N concentrations around 30 to 38 g kg<sup>-1</sup> and a maximum SPAD reading of 60.

### **Corn Yields**

Generally, the desired effect of adding N fertilizer to grain crops is to increase yields and SLL previously has been shown to be a valuable N source for plant growth. In 2000, additions of N from SLL or NH<sub>4</sub>NO<sub>3</sub> consistently increased corn yields (Figs 3.9, and 3.10). Surprisingly, in 1999 corn yields did not significantly increase with N additions except for Section 1 (Fig 3.9). Because the additions of N were proportional to the SLL irrigation depths, the overall effects of N applications on corn yields in Section 1 cannot be determined. It appears that water may have been limiting at the low N application rates in Section 1, especially in 1999, since corn yields were higher in Section 2 (Fig. 3.10) at the same N rates. Given the positive yield responses to SLL additions in 2000 (Fig. 3.10), enough residual soil N became available in 1999 such that yields were not reduced because of N deficiency. High concentrations of residual soil N may have been present due to SLL applications in previous years.

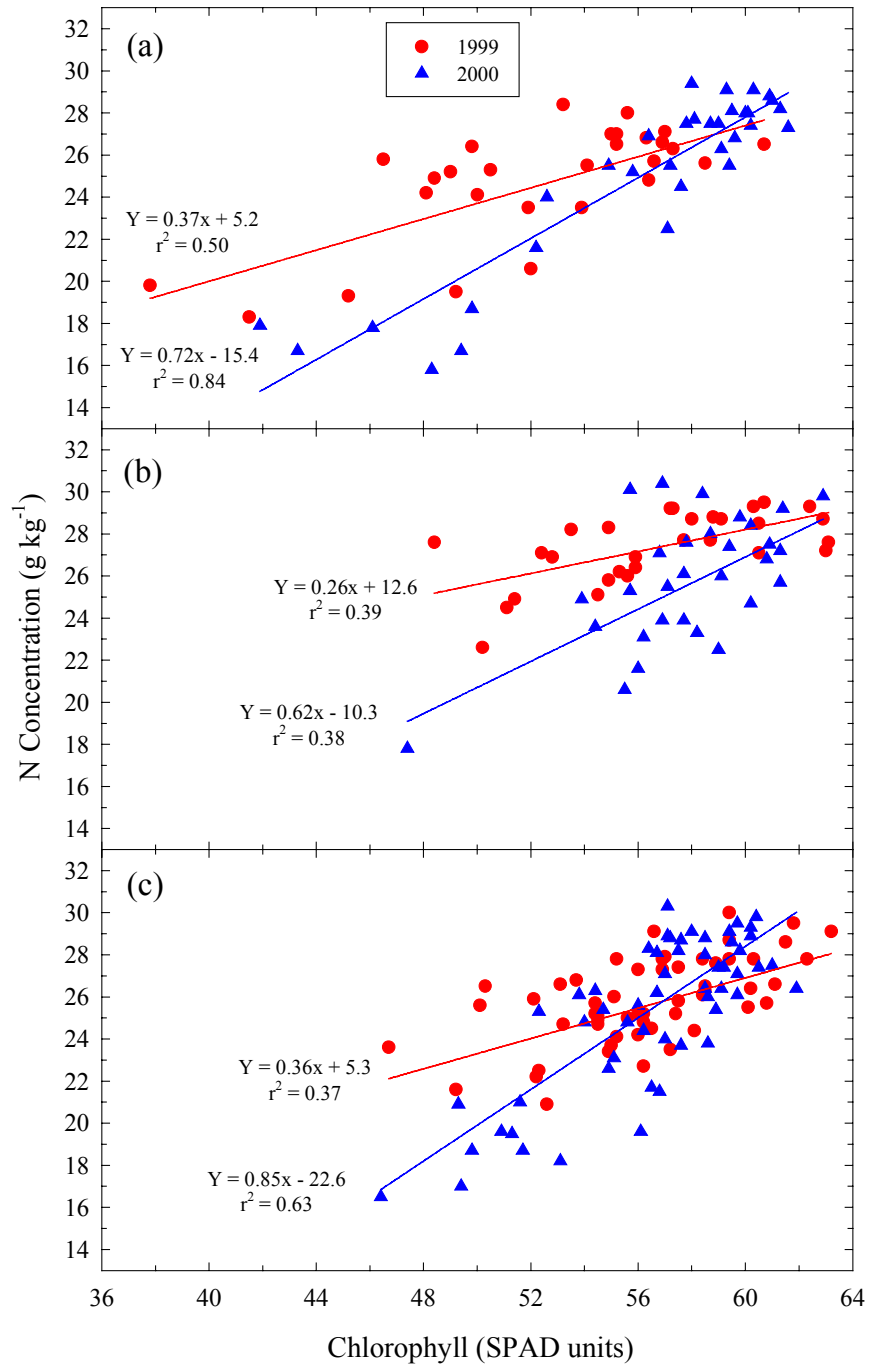


Fig. 3.8. Chlorophyll meter readings of the corn ear leaf as a predictor of leaf N concentrations in 1999 and 2000 for (a) Section 1, (b) Section 2, and (c) Section 3.

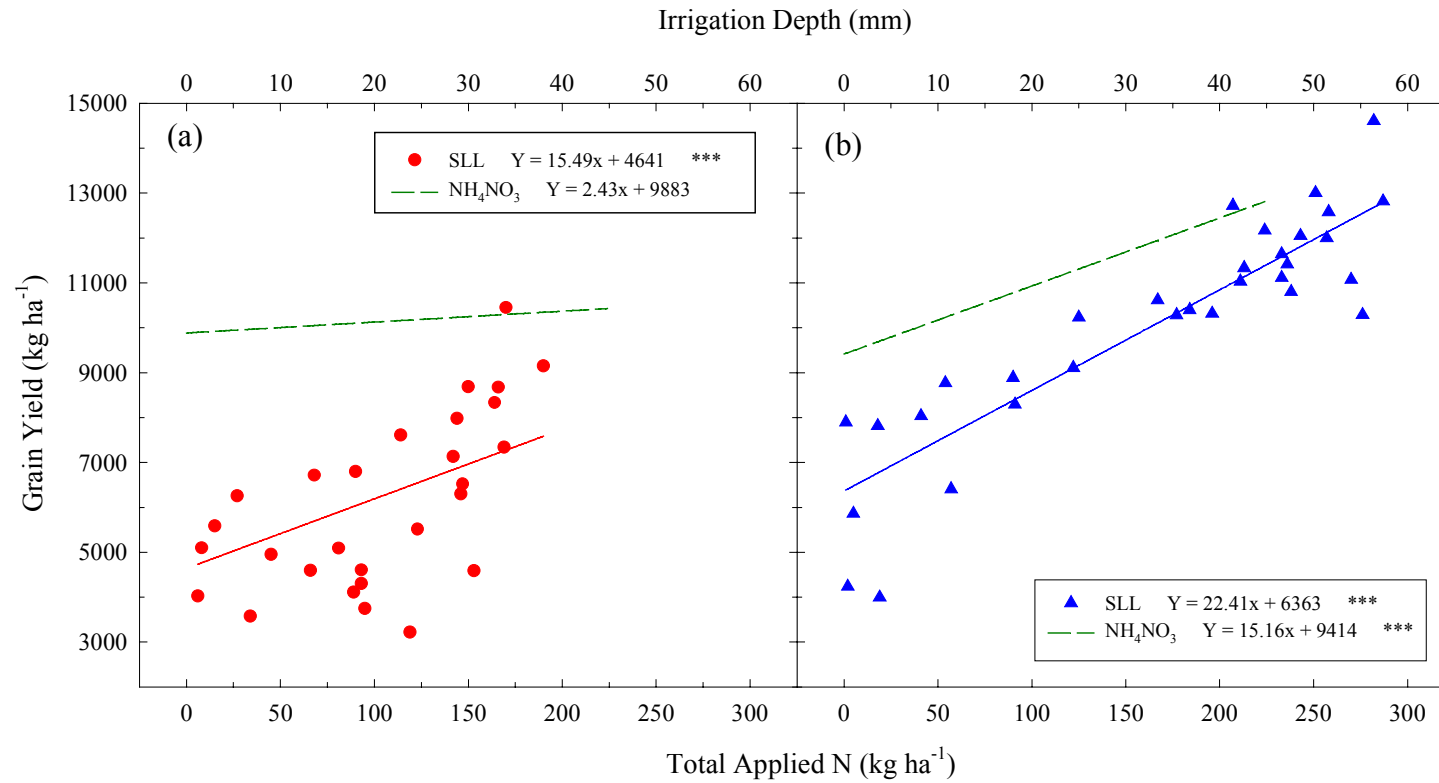


Fig. 3.9. Corn yields in (a) 1999 and (b) 2000 as influenced by SLL additions in Section 1 and fertilizer applications in Section 3. Irrigation depth pertains only to SLL applications. Fertilizer treatments received 20 to 40 mm of water in 1999 and 40 to 50 mm in 2000. \*\*\* indicates slope significant at the 0.001 probability level.

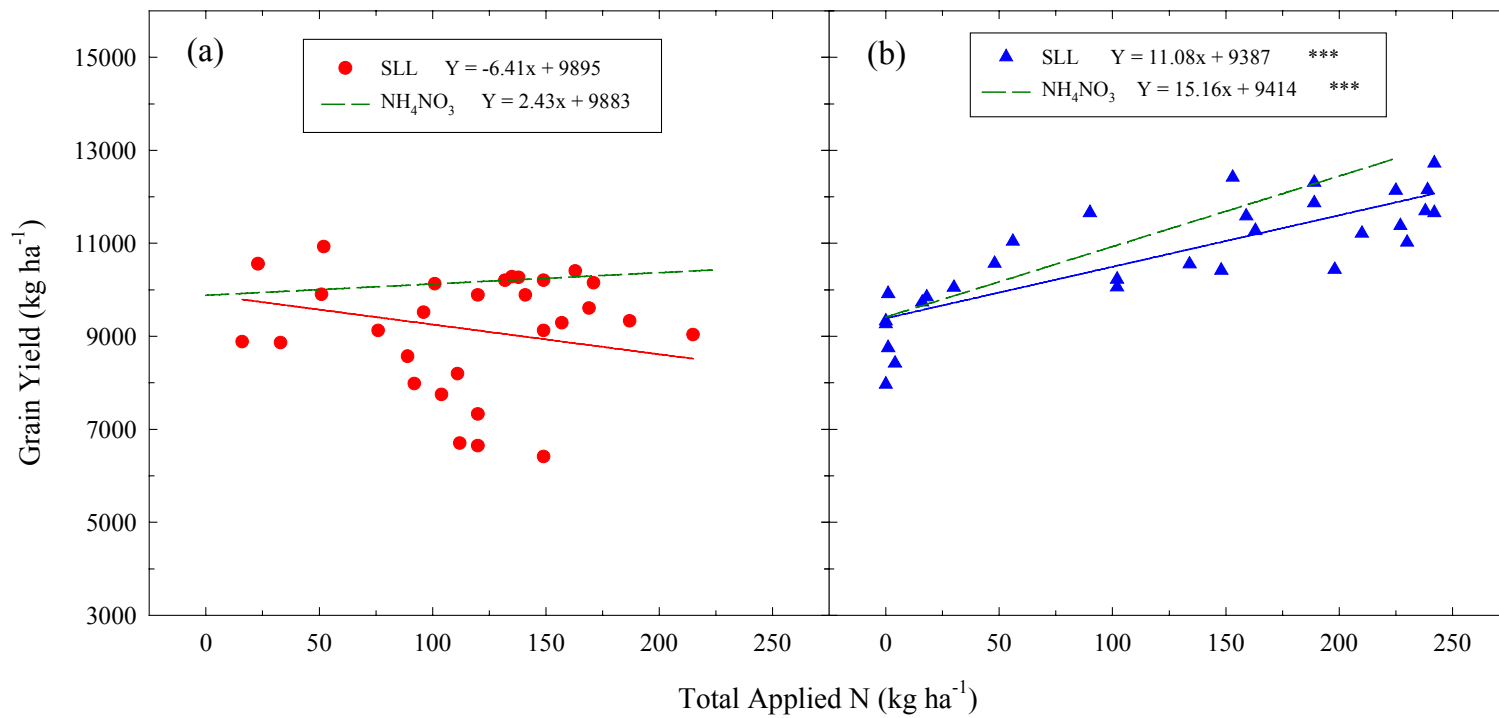


Fig. 3.10. Corn yields in (a) 1999 and (b) 2000 as influenced by SLL additions in Section 2 and fertilizer applications in Section 3. Irrigation depths for the fertilizer treatments ranged from 20 to 40 mm in 1999 and 40 to 50 mm in 2000. Irrigation depths in Section 2 ranged from 30 to 60 mm in 1999 and 50 to 80 mm in 2000. \*\*\* indicates slope significant at the 0.001 probability level.

In 1999 and 2000, the addition of irrigation water significantly affected corn yields in the fertilizer treatments in Section 3. When all irrigation depths in 1999 (0 – 40 mm) were considered, a negative yield response to  $\text{NH}_4\text{NO}_3$  additions was noticed (Fig. 3.11). However, when only the highest irrigation depths (20 – 40 mm) were considered, the irrigation effect was removed and a positive yield response to  $\text{NH}_4\text{NO}_3$  additions in 1999 was obtained. The positive response curve to  $\text{NH}_4\text{NO}_3$  additions is presented in Figures 3.9 and 3.10 for a comparison to SLL additions in 1999. The yield response curve to  $\text{NH}_4\text{NO}_3$  applications in 2000 (Fig. 3.9 and 3.10) also represents only the highest irrigation depths (40 to 50 mm) for that year.

Other possible reasons for the lack of fertilizer response in 1999 are the timing of the second fertilizer application and the method of application. The second fertilizer application was applied right before the corn went into its reproductive stage. This was also the timing of the second SLL application. Because of the late applications, the corn may not have been able to utilize the applied N for grain production. By the start of the reproductive stage, approximately 60% of the plant N has been taken up (Aldrich et al., 1975). Also in 1999, the  $\text{NH}_4\text{NO}_3$  was broadcasted by using a drop spreader centered over the furrow versus in 2000 when the fertilizer was banded by the row.

Previous research on corn yield response to fertilizer N additions shows that yields tend to plateau around  $168 \text{ kg N ha}^{-1}$  (Schepers et al., 1992; Wood et al., 1992; Fox and Piekielek, 1987; Kamprath, 1986). The yield response to fertilizer in 2000 comes the closest to having a quadratic term (Fig. 3.11). The high yields recorded at the 0 and  $56 \text{ kg N ha}^{-1}$  are not typical of previous fertilizer studies where lower yields are observed at those rates. Similarly, no plateau was noticed for

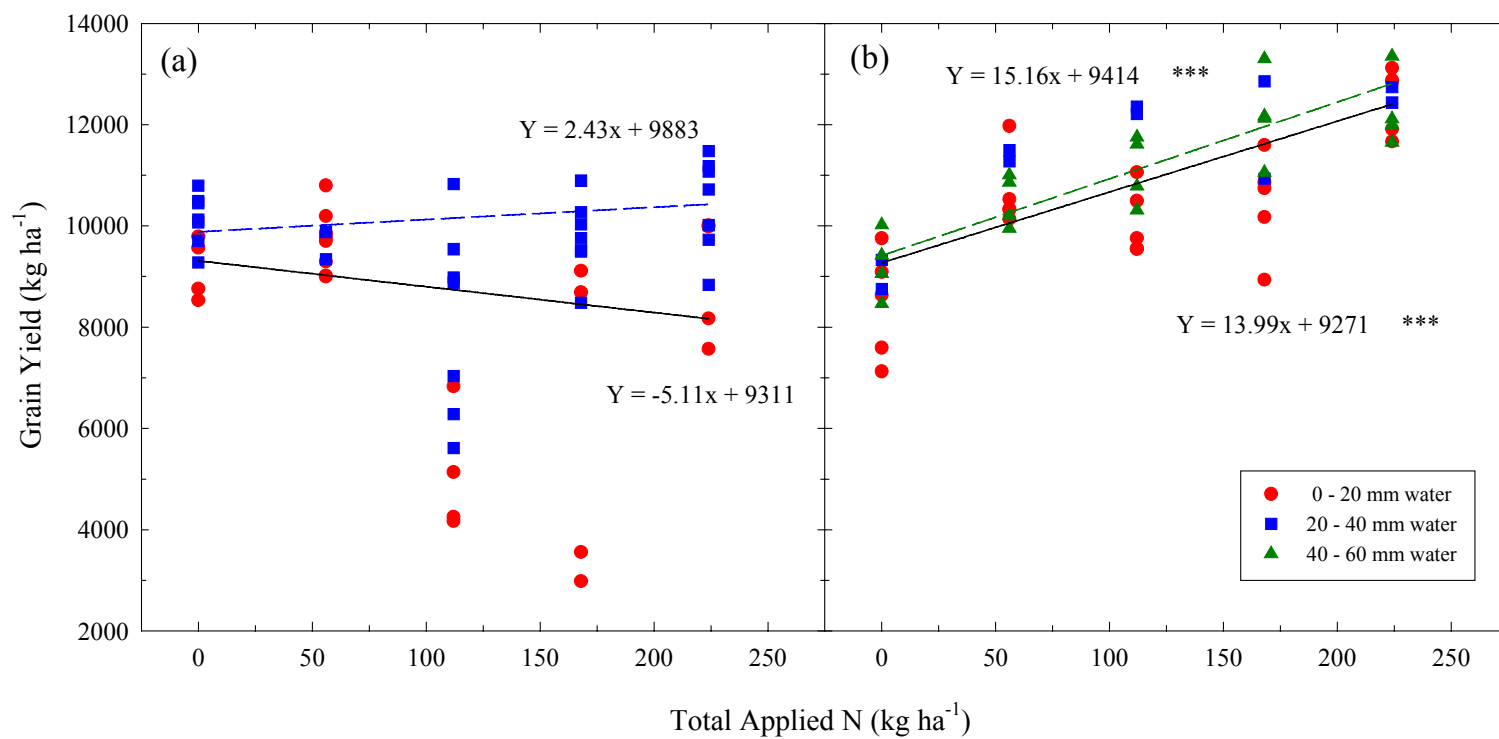


Fig. 3.11. Corn yields for Section 3 in response to increases in  $\text{NH}_4\text{NO}_3$  rates and water irrigation depths in (a) 1999 and (b) 2000. \*\*\* indicates slope significant at the 0.001 probability level.

the N applied from the SLL. As noticed with leaf N concentrations, the amount of applied N from the SLL appears to be less effective than  $\text{NH}_4\text{NO}_3$  in 2000. Corn yield from SLL applied at  $200 \text{ kg N ha}^{-1}$  in Section 1 (Fig. 3.9) is about 1,600 kg lower than the same  $\text{NH}_4\text{NO}_3$  rate for 2000. Approximately  $71 \text{ kg N ha}^{-1}$  in additional SLL would be needed to obtain similar yields as reached by applying  $\text{NH}_4\text{NO}_3$  at  $200 \text{ kg N ha}^{-1}$ . Therefore after irrigation, N from SLL after irrigation was about 74% as effective as  $\text{NH}_4\text{NO}_3$  in increasing corn yields.

While the slopes between the SLL in Section 2 (Fig. 3.10) and the fertilizer treatment were not significantly different in 2000, the fertilizer treatment resulted in a corn yield about 700 kg higher than SLL at  $168 \text{ kg N ha}^{-1}$ . About  $64 \text{ kg N ha}^{-1}$  in additional SLL would be needed to obtain an equivalent yield from fertilizer applied at  $168 \text{ kg N ha}^{-1}$ . The extra SLL needed to reach an equivalent yield suggests that the N in SLL was  $\approx 73\%$  as effective as  $\text{NH}_4\text{NO}_3$  in increasing corn yields in 2000. However, at applications  $<150 \text{ kg N ha}^{-1}$  (Fig. 3.10), the difference between yield response from SLL and  $\text{NH}_4\text{NO}_3$  was not that great. It is not known whether this is due to residual soil N concentrations or better plant utilization of applied N from SLL at the lower rates. Since the yields were similar at  $0 \text{ kg N ha}^{-1}$  for SLL and  $\text{NH}_4\text{NO}_3$  (Fig. 3.10), residual soil N concentrations should be the same for both treatments.



## Soybean Yields

The additions of N from SLL had no significant impact on soybean (SB) grain yield response (Figs. 3.12 and 3.13) in 1999 or 2000. Only fertilizer N additions in 2000 significantly increased soybean yields (Fig 3.14). The irrigation effect on soybean yields in the fertilizer treatments (Section 3) was not significant in either 1999 or 2000. In 2000, soybean yield response to SLL additions in Section 1 (Fig. 3.12) and Section 2 (Fig 3.13) were similar, thus suggesting that irrigation depth had no significant influence on yield response in Section 1. Also in 2000, soybean yield response to  $\text{NH}_4\text{NO}_3$  was significantly ( $p < 0.05$ ) higher than yield response to SLL in Section 1 or Section 2. The yield difference between SLL and  $\text{NH}_4\text{NO}_3$  additions may have been influenced by the reduction in biomass production due to deer grazing in Section 3. A 60% reduction in plant biomass between Section 1 and Section 3 two months after planting was recorded. Also, the soybeans receiving the higher rates of SLL were more susceptible to lodging than were the soybeans receiving  $\text{NH}_4\text{NO}_3$ . The lack of a yield response to N additions is not uncommon since soybean have the ability to obtain N from symbiotic  $\text{N}_2$  fixation. To determine the amount of applied N the soybean are utilizing, some measurement of  $\text{N}_2$  fixation is needed (see Chapter 4).

In 2000, a nonnodulating soybean isolate was incorporated into the experiment to assist in determining the potential for soybean to be used as a receiver crop for SLL (see Chapter 4). Grain yields from the nonnodulating soybean (NSB) increased significantly from additions of  $\text{NH}_4\text{NO}_3$  (Fig. 3.14) or SLL in Section 1 (Fig. 3.12) and 2 (Fig. 3.13). Unlike corn yield responses to applied N in 2000, the nonnodulating soybean responded similarly to applied N from SLL in Section 2 (Fig 3.13) or  $\text{NH}_4\text{NO}_3$ .

The similarity in nonnodulating soybean yields from SLL and  $\text{NH}_4\text{NO}_3$  additions in 2000 implies that applied N from SLL was no different from  $\text{NH}_4\text{NO}_3$ . However in Section 1 (Fig. 3.12), nonnodulating soybean grain response was about 300 kg higher for the fertilizer treatment than the SLL at 200 kg N ha<sup>-1</sup>. To reach the same yield with SLL, 98 kg N ha<sup>-1</sup> more SLL would need to be added. Thus, SLL was about 67% as effective as  $\text{NH}_4\text{NO}_3$  in increasing yields of the nonnodulating soybean.

When comparing the relative yield of corn to nonnodulating soybean in response to SLL applications in Section 2 or fertilizer additions, the nonnodulating soybean was twice as effective in utilizing the applied N as corn. In 2000, increases in yields of 24 and 56% for corn and nonnodulating soybean respectively were obtained as SLL additions increased from 0 to 200 kg N ha<sup>-1</sup> in Section 2. At the same application range for  $\text{NH}_4\text{NO}_3$ , yields increased 32 and 73% for corn and nonnodulating soybean respectively. Therefore, while nonnodulating soybean may have lower absolute yields than corn; the nonnodulating soybean may utilize more of the applied N.

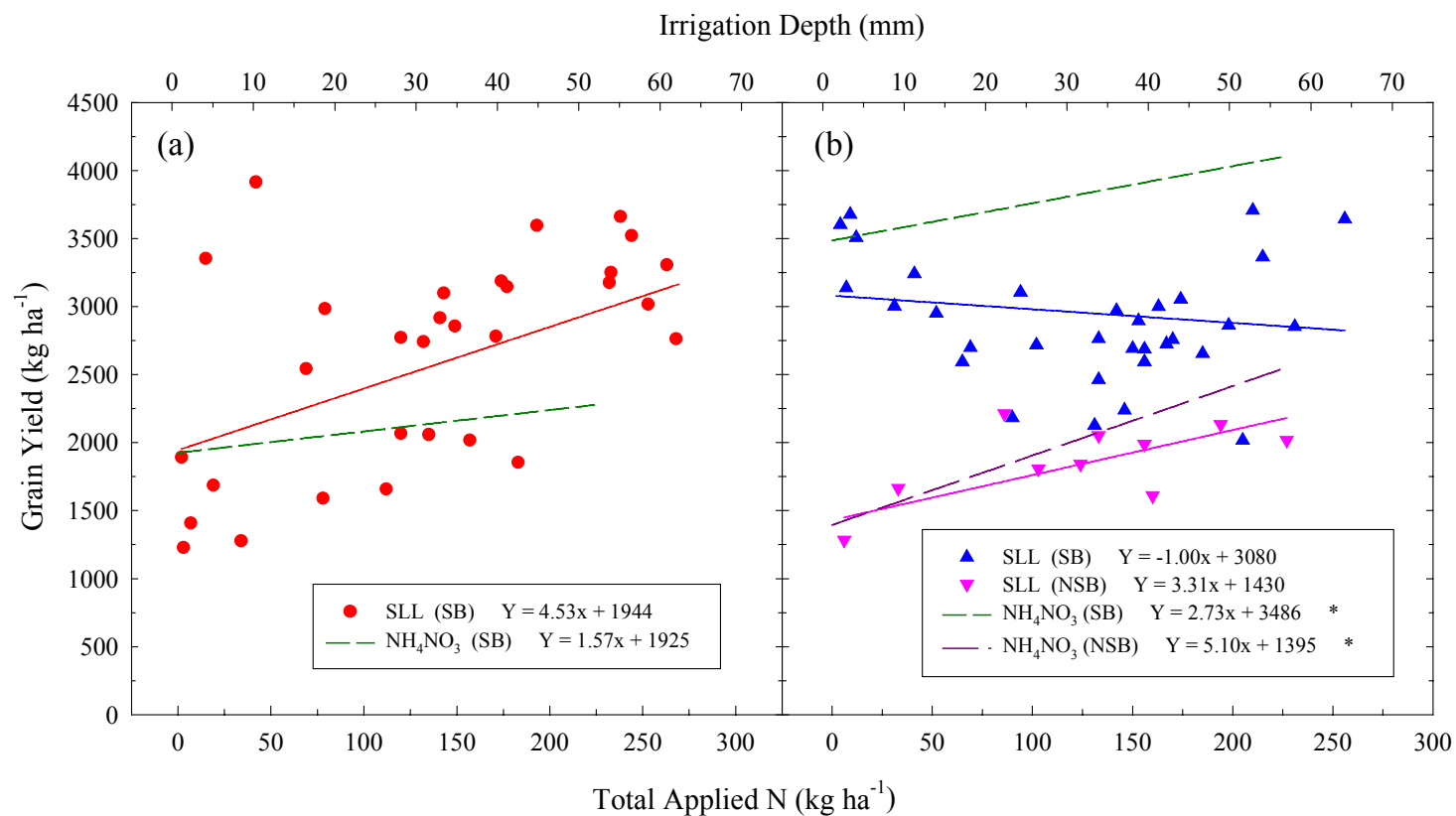


Fig. 3.12. Soybean (SB) and nonnodulating soybean (NSB) yields in (a) 1999 and (b) 2000 as influenced by SLL additions in Section 1 and fertilizer applications in Section 3. Irrigation depth pertains only to SLL additions. \* indicates slope significant at the 0.05 probability level.

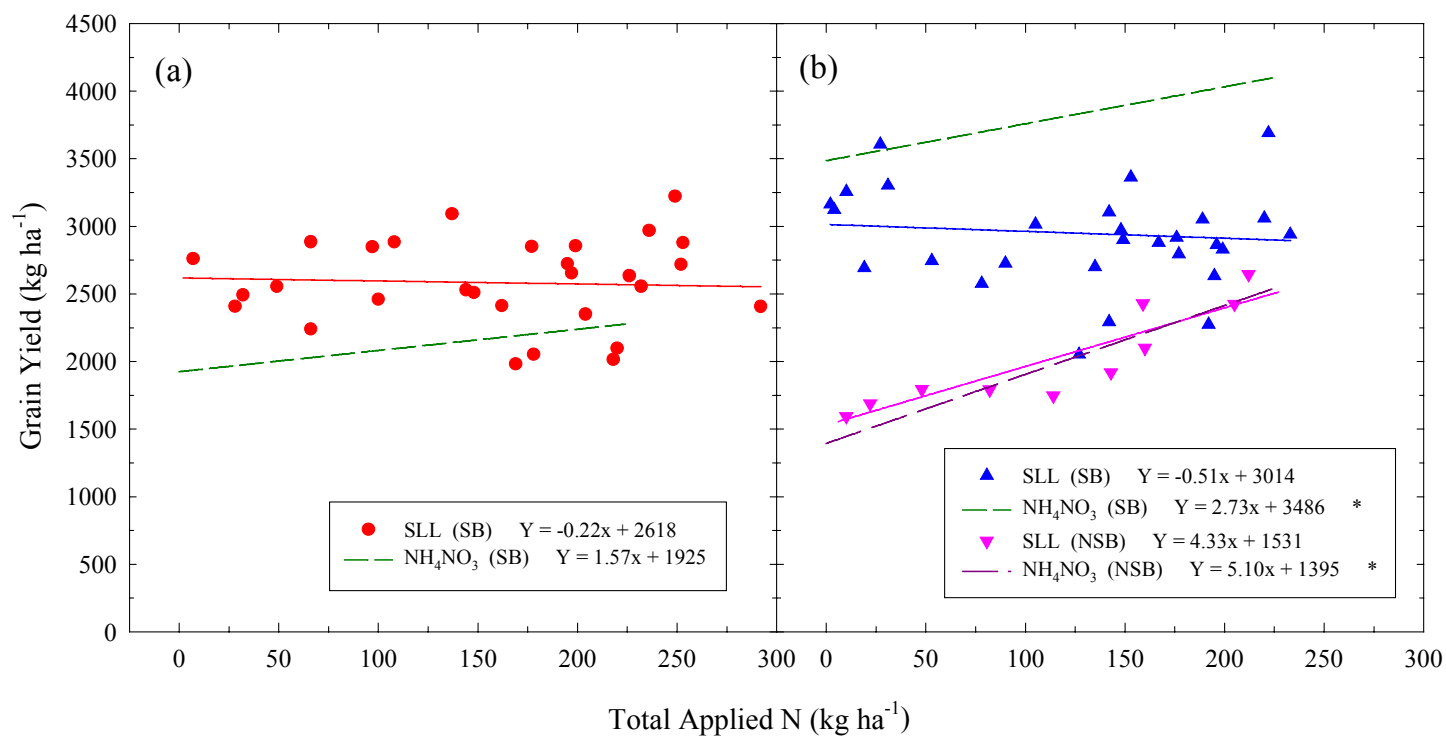


Fig. 3.13. Soybean (SB) and nonnodulating soybean (NSB) yields in (a) 1999 and (b) 2000 as influenced by SLL additions in Section 2 and fertilizer applications in Section 3. Irrigation depths ranged from 40 to 80 mm in Section 2 for both years. \* indicates slope significant at the 0.05 probability level.

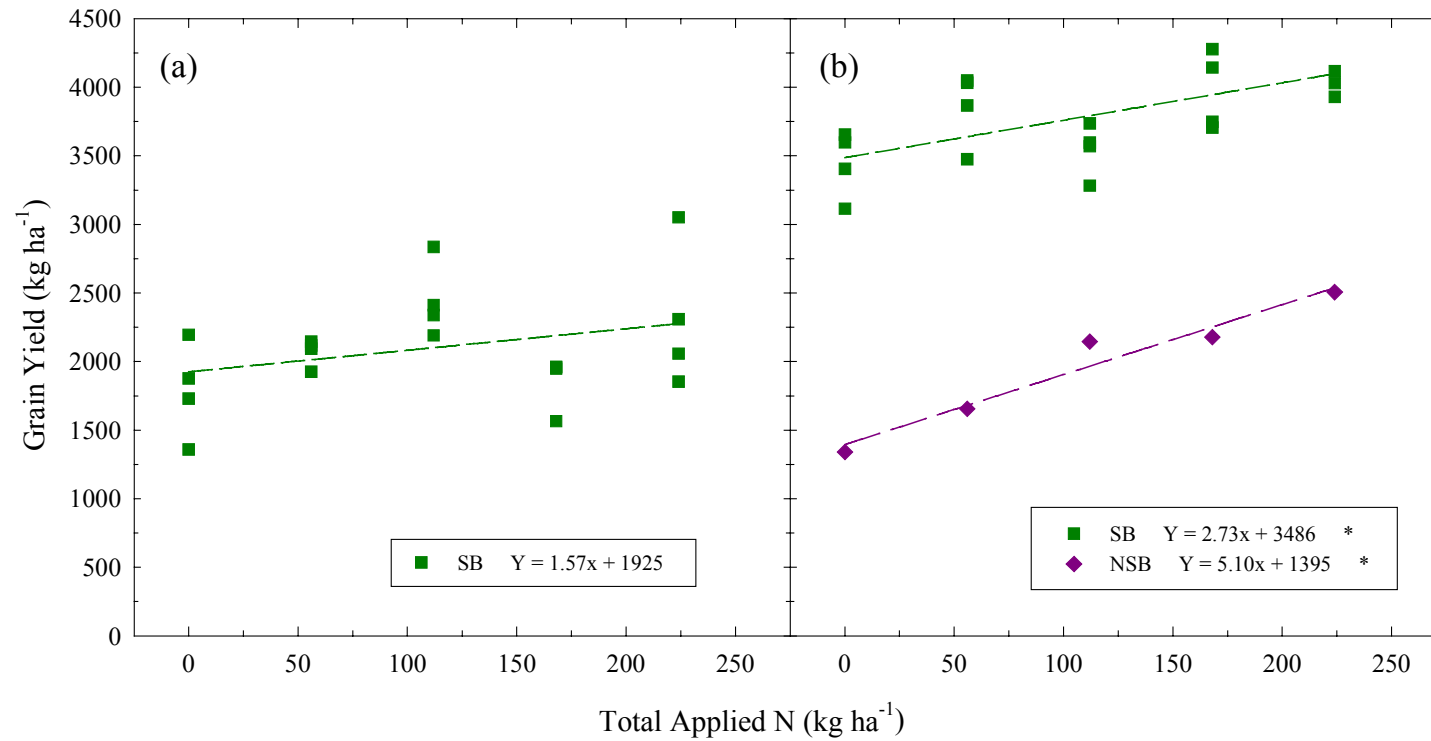


Fig. 3.14. Soybean (SB) and nonnodulating soybean (NSB) yields for Section 3 in response to  $\text{NH}_4\text{NO}_3$  additions in (a) 1999 and (b) 2000. Irrigation depth ranged from 0 to 60 mm in 1999 and 0 to 70 mm in 2000 for soybean. Fertilizer treatments to NSB were not irrigated. \* indicates slope significant at the 0.05 probability level.

### Grain Nitrogen Recovery

Corn seed N concentrations ranged from 12 to 17 g kg<sup>-1</sup> in 1999 and 9 to 16 g kg<sup>-1</sup> in 2000 for all sections (Fig. 3.15 and 3.16). The higher seed N concentrations at the 0 kg N ha<sup>-1</sup> application in 1999 was attributed to residual soil N. A quadratic function was used to describe seed N concentrations in 2000. The maximum N concentration was obtained around 168 kg ha<sup>-1</sup> of applied N for all sections (Fig. 3.15 and 3.16) in 2000. The sections (1, 2, and 3) were not significant different within either year. Section 2 (Fig. 3.16) was significantly ( $p < 0.05$ ) affected by irrigation in 2000. However, with an application depth range of 50 to 80 mm in Section 2, the high and low rates of SLL received equal amounts of water. The highest irrigation depths were located in the center of Section 2 (see Fig. 2.7 and 2.8 for irrigation amounts in Section 2). The NH<sub>4</sub>NO<sub>3</sub> treatments had an irrigation range of 0 to 50 cm and were not significantly affected by irrigation depths.

With the nodulating soybean, a slight decrease in seed N concentrations with increasing amounts of applied N from SLL was found for Sections 1 and 2 in both years (Fig. 3.17 and 3.18). This was opposite from the fertilizer N application in which had a slight increase in seed N concentration with increasing N amounts. Altogether, the seed N concentrations for the nodulating soybean ranged from 59 to 63 g kg<sup>-1</sup> in 1999 and 61 to 66 g kg<sup>-1</sup> in 2000 (Fig. 3.17 and 3.18). The seed N concentration of the nonnodulating soybean in 2000 increased with N applied from either SLL or NH<sub>4</sub>NO<sub>3</sub>. For Section 1 (Fig. 3.17), a quadratic function was significant in describing nonnodulating soybean seed N response to SLL additions. With the quadratic function, seed N concentration plateau at 56 g kg<sup>-1</sup> as N application reached 168 kg ha<sup>-1</sup>.

However, a quadratic function was not significant for Section 2 (Fig. 3.18) and the fertilizer treatment. The difference between Section 1 and 2 was probably due to the increasing irrigation depths that corresponded to increasing N rates in Section 1. The nonnodulating soybeans receiving the fertilizer treatments were not irrigated with water.

Total N recovered by harvesting the grain from either corn or soybean was similar with increasing amounts of applied N in 1999 except for Section 1 (Fig. 3.19 and 3.20). Based on total grain N removed, soybean removed significantly more N than did corn with increasing rates of N. However, nitrogen use efficiencies (NUE) were <15% for both crops at an application rate of 168 kg N ha<sup>-1</sup> for SLL in Section 2 or NH<sub>4</sub>NO<sub>3</sub> (Fig. 3.19 and 3.20). The NUE was determined by the equation (Bock, 1984):

$$[(NR_i - NR_o) / N_i] * 100$$

where

$NR_i$  is the N recovered (grain) at a specific applied N rate ( $i$ );

$NR_o$  is the N recovered (grain) from the control (0 kg N ha<sup>-1</sup> applied); and

$N_i$  is the applied N at ( $i$ ).

For soybean, the estimated amount of N fixed based on C<sub>2</sub>H<sub>2</sub> reduction activity (see Results and Discussion in Chapter 4) was added to  $NR_o$  and subtracted from  $NR_i$  to get the amount of N recovered from the applied nitrogen ( $N_i$ ). The insignificant increase in grain N recovery with SLL or NH<sub>4</sub>NO<sub>3</sub> additions in 1999 supports the theory that significant N was made available through mineralization of soil organic N.

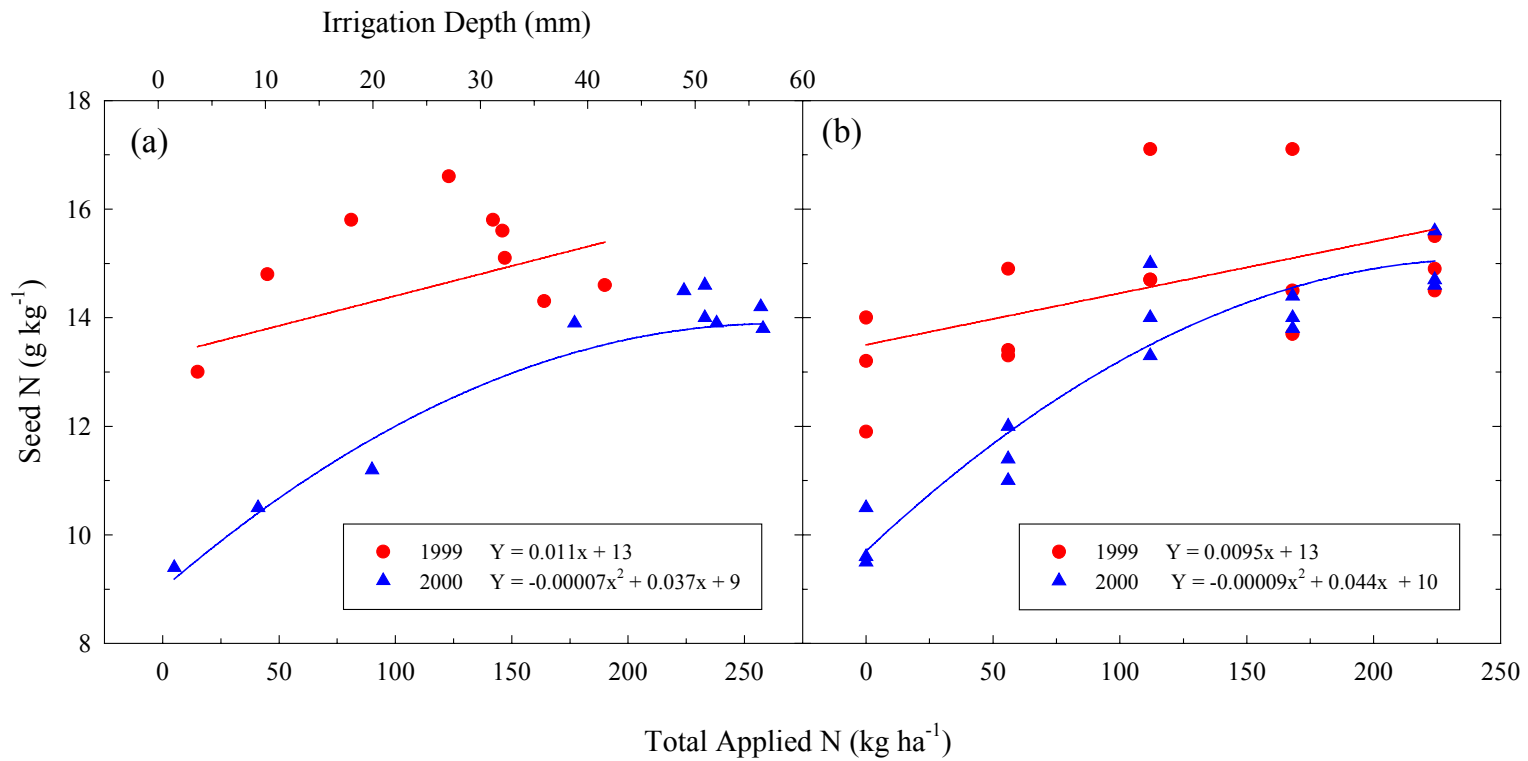


Fig. 3.15. Seed N concentrations of corn fertilized with SLL in (a) Section 1 and (b) NH<sub>4</sub>NO<sub>3</sub> in Section 3. Fertilizer treatments received 20 to 40 mm of water in 1999 and 40 to 50 mm in 2000.



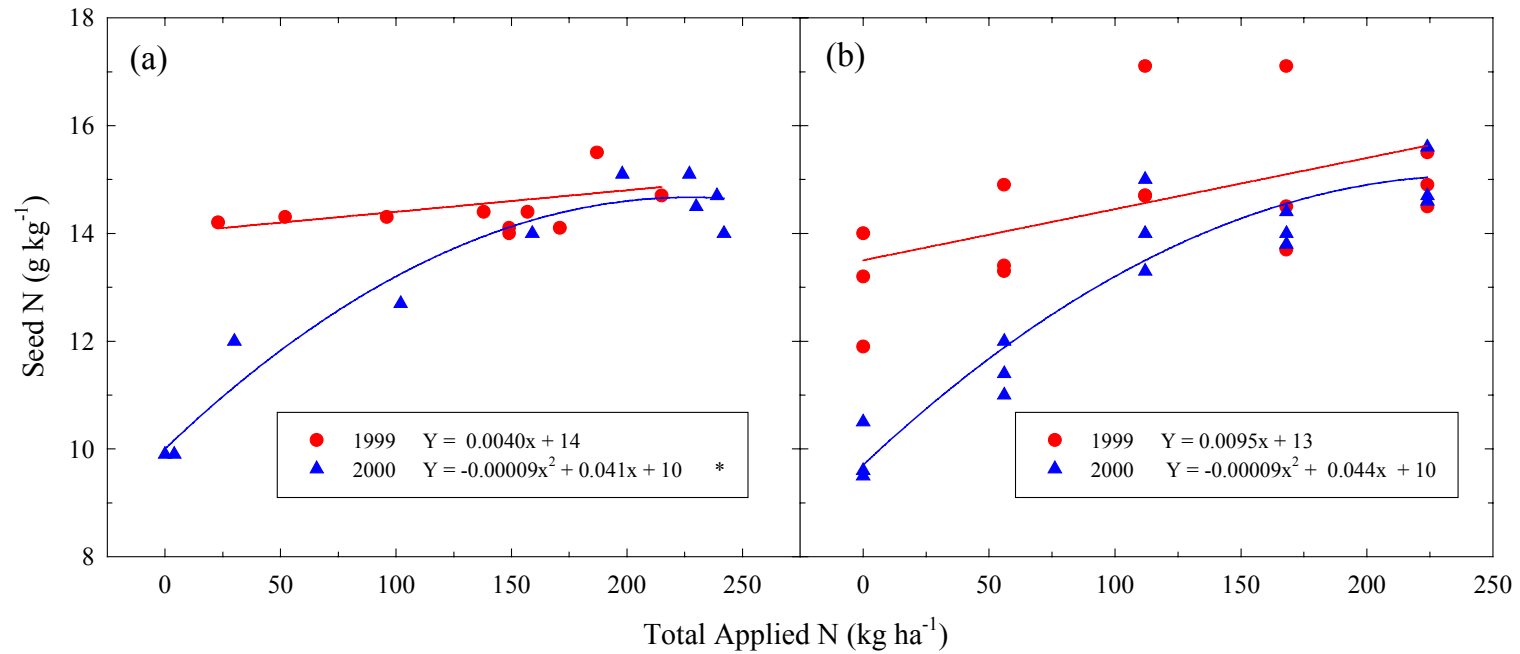


Fig. 3.16. Seed N concentrations of corn fertilized with SLL in (a) Section 2 and (b) NH<sub>4</sub>NO<sub>3</sub> in Section 3. Irrigation depths for the fertilizer treatments ranged from 20 to 40 mm in 1999 and 40 to 50 mm in 2000. Irrigation depths in Section 2 ranged from 30 to 60 mm in 1999 and 50 to 80 mm in 2000. \* indicates slope significant at the 0.05 probability level.

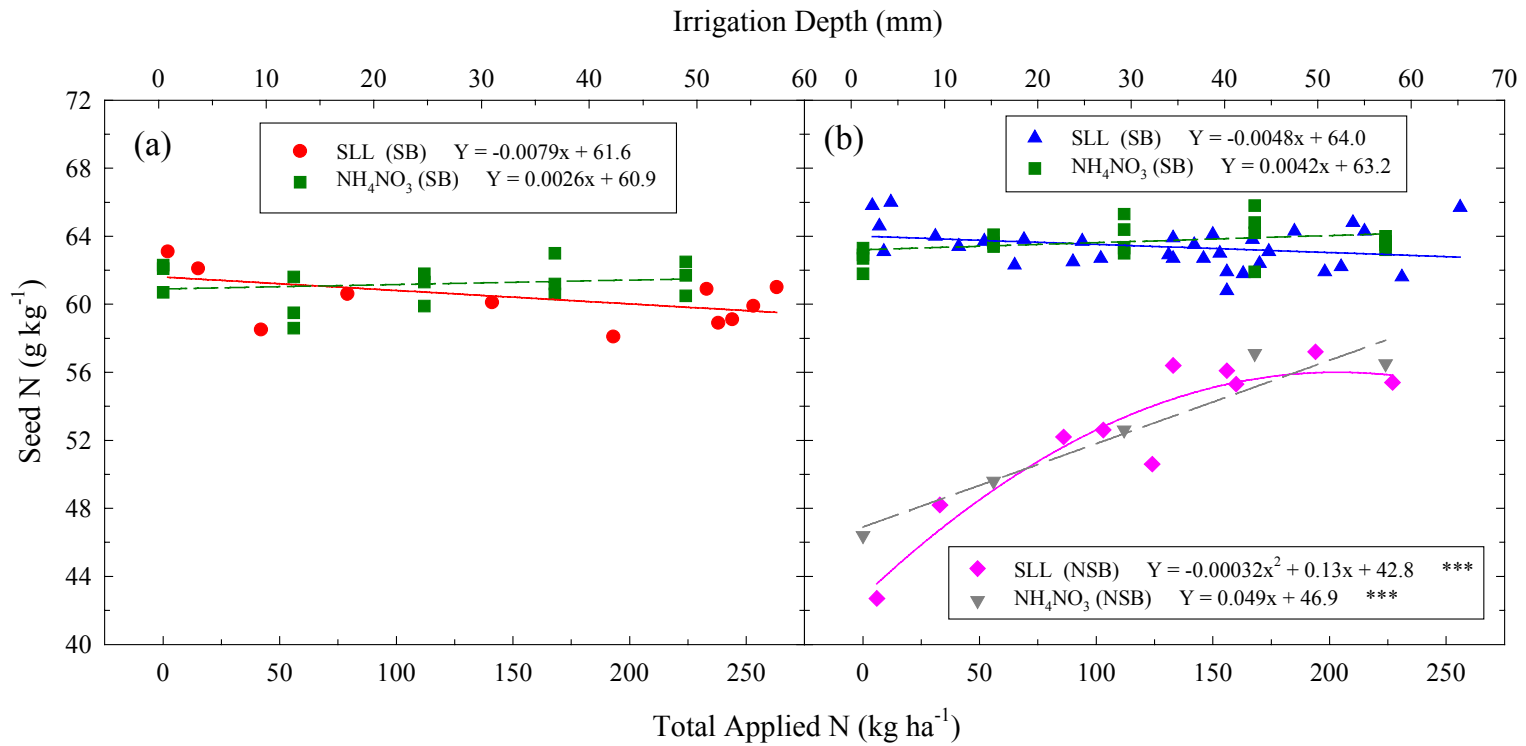


Fig. 3.17. Seed N concentrations from soybean (SB) and nonnodulating soybean (NSB) in response to SLL additions in Section 1 and NH<sub>4</sub>NO<sub>3</sub> applications in (a) 1999 and (b) 2000. Irrigation depths for the fertilizer plots ranged from 0 to 70 mm for the SB and 0 mm for the NSB. \*\*\* indicates slope significant at the 0.001 probability level.

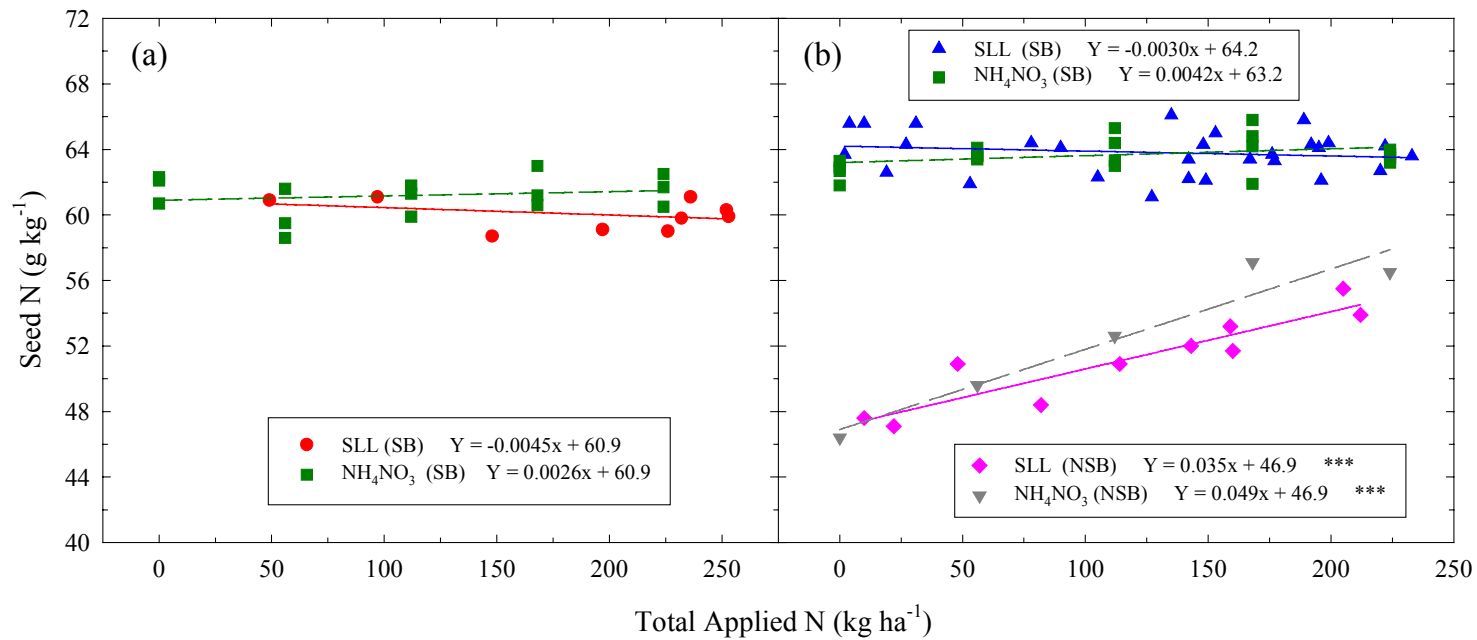


Fig. 3.18. Seed N concentrations from soybean (SB) and nonnodulating soybean (NSB) in response to SLL additions in Section 2 and NH<sub>4</sub>NO<sub>3</sub> applications in (a) 1999 and (b) 2000. Irrigation depths for Section 2 ranged from 40 to 80 mm and 0 to 70 mm for the SB fertilizer plots. NSB receiving NH<sub>4</sub>NO<sub>3</sub> were not irrigated. \*\*\* indicates slope significant at the 0.001 probability level.

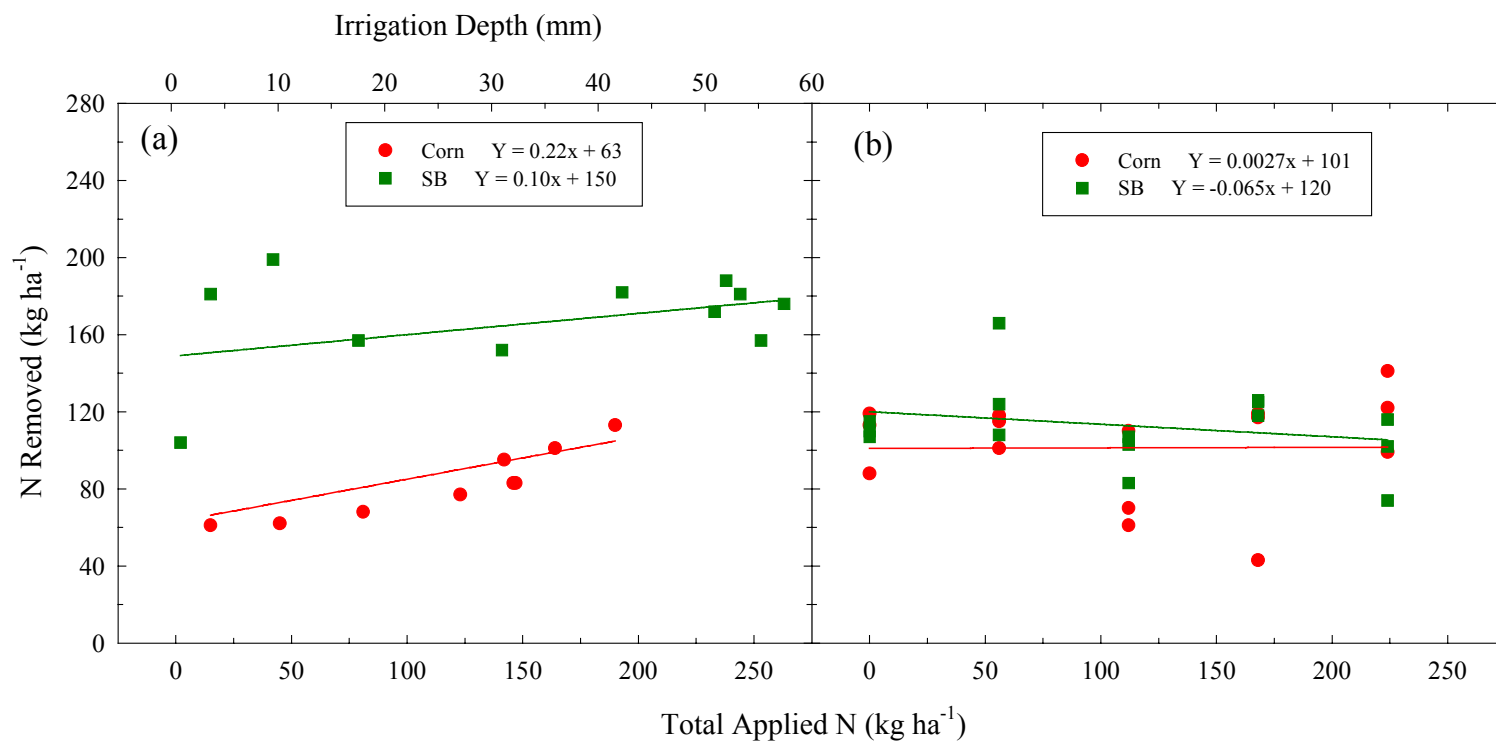


Fig. 3.19. Removal of grain N by corn and soybean (SB) in 1999 from SLL additions in (a) Section 1 and (b) NH<sub>4</sub>NO<sub>3</sub> applications in Section 3.

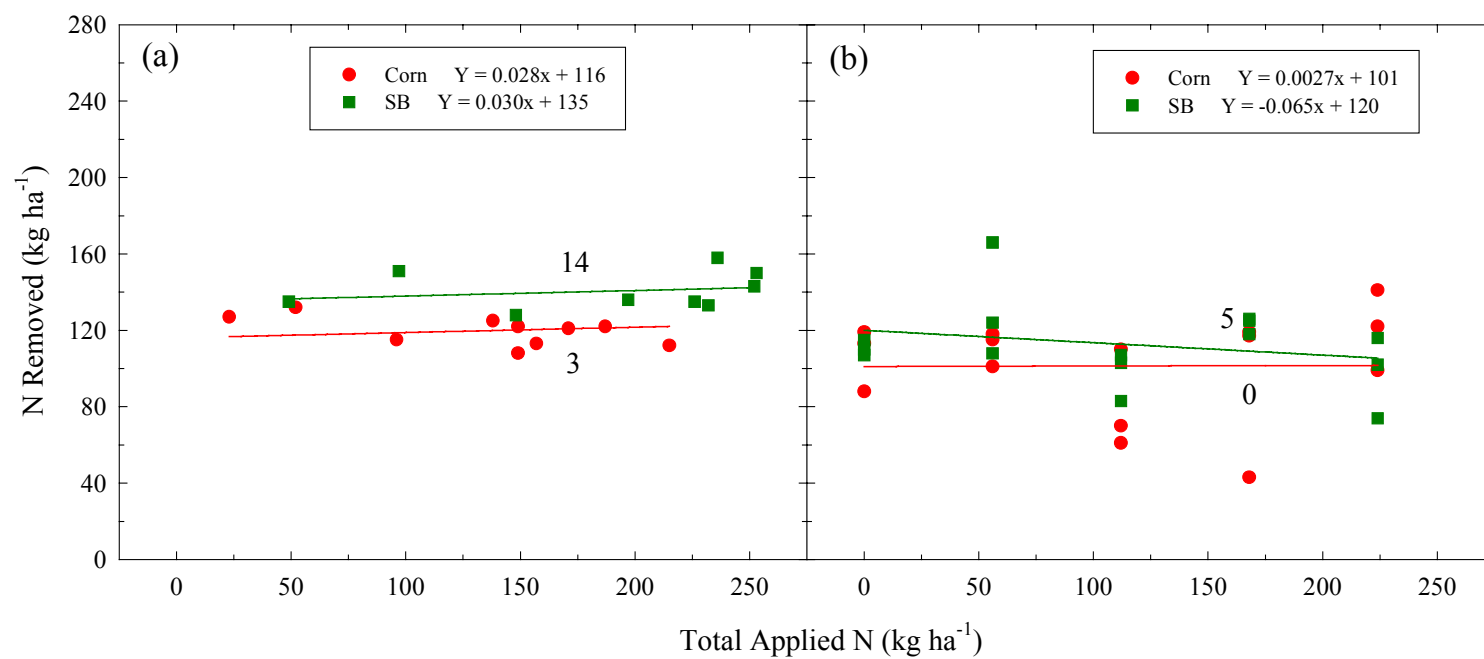


Fig. 3.20. Removal of grain N by corn and soybean (SB) in 1999 in response to SLL additions in (a) Section 2 and (b)  $\text{NH}_4\text{NO}_3$  applications in Section 3. Numbers on the graph are the NUE at an application rate of 168 kg N ha<sup>-1</sup>.

In 2000, both corn and nonnodulating soybean accumulated more grain N as applied N increased (Fig. 3.21 and 3.22). Grain N recovered by corn or nonnodulating soybean was only significantly different in Section 1. The nodulating soybean removed similar amounts of grain N with increasing amounts of SLL-applied N. With the  $\text{NH}_4\text{NO}_3$  additions to nodulating soybean, a significant increase in N removed was noticed as the application rate increased in 2000. Therefore, greater grain N recovery from the nodulating soybean was obtained by N supplied from  $\text{NH}_4\text{NO}_3$  than SLL.

The NUE increased in 2000, suggesting better crop utilization of applied N. With SLL supplying  $168 \text{ kg N ha}^{-1}$ , NUEs were 28% for corn, 25% for nonnodulating soybean, and 39% for nodulating soybean. With  $\text{NH}_4\text{NO}_3$  supplying the same N rate, NUEs were higher: corn, 45%; nonnodulating soybean, 31%; and nodulating soybean, 56%. The NUE of 45% calculated for corn is similar to NUEs reported from other research (Wiesler, 1998; Kamprath, 1986; Bock, 1984). However, the NUE of 31% for the nonnodulating soybean was lower than the NUE of 69% reported by Israel and Mikkelsen (1998) for the same soybean isoline at  $112 \text{ kg N ha}^{-1}$  of  $\text{NH}_4\text{NO}_3$ . Based on NUE, the nodulating soybean appears to use either SLL or  $\text{NH}_4\text{NO}_3$  more effectively than do corn or nonnodulating soybean. However, the NUE for the nodulating soybean is merely an estimate since the amount of N fixed was estimated and not quantitatively measured.

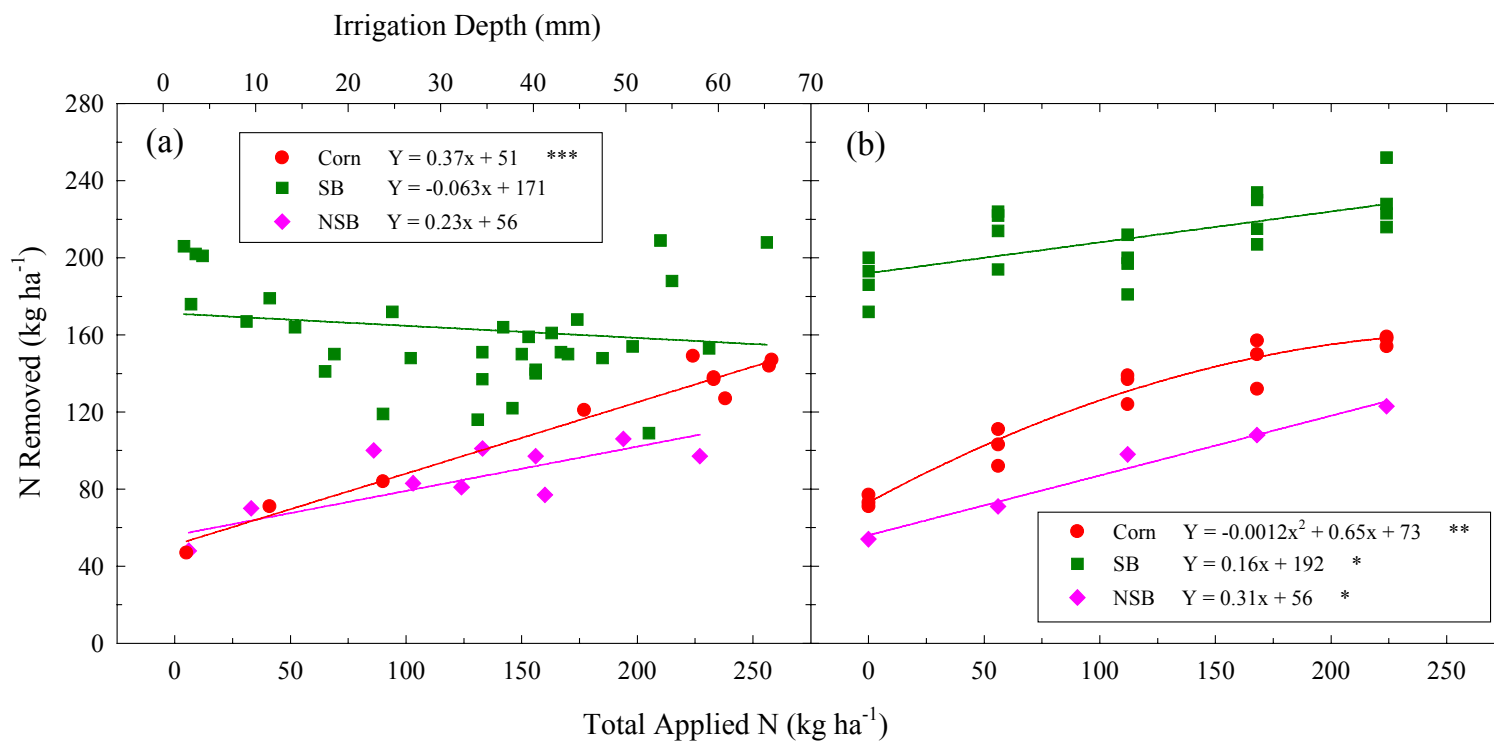


Fig. 3.21. Grain N removal by corn, soybean (SB), and nonnodulating soybean (NSB) in 2000 from SLL additions in (a) Section 1 and (b) NH<sub>4</sub>NO<sub>3</sub> applications in Section 3. \*\*\*, \*\*, \* indicate slopes significant at the 0.001, 0.01, and 0.05 probability levels respectively.

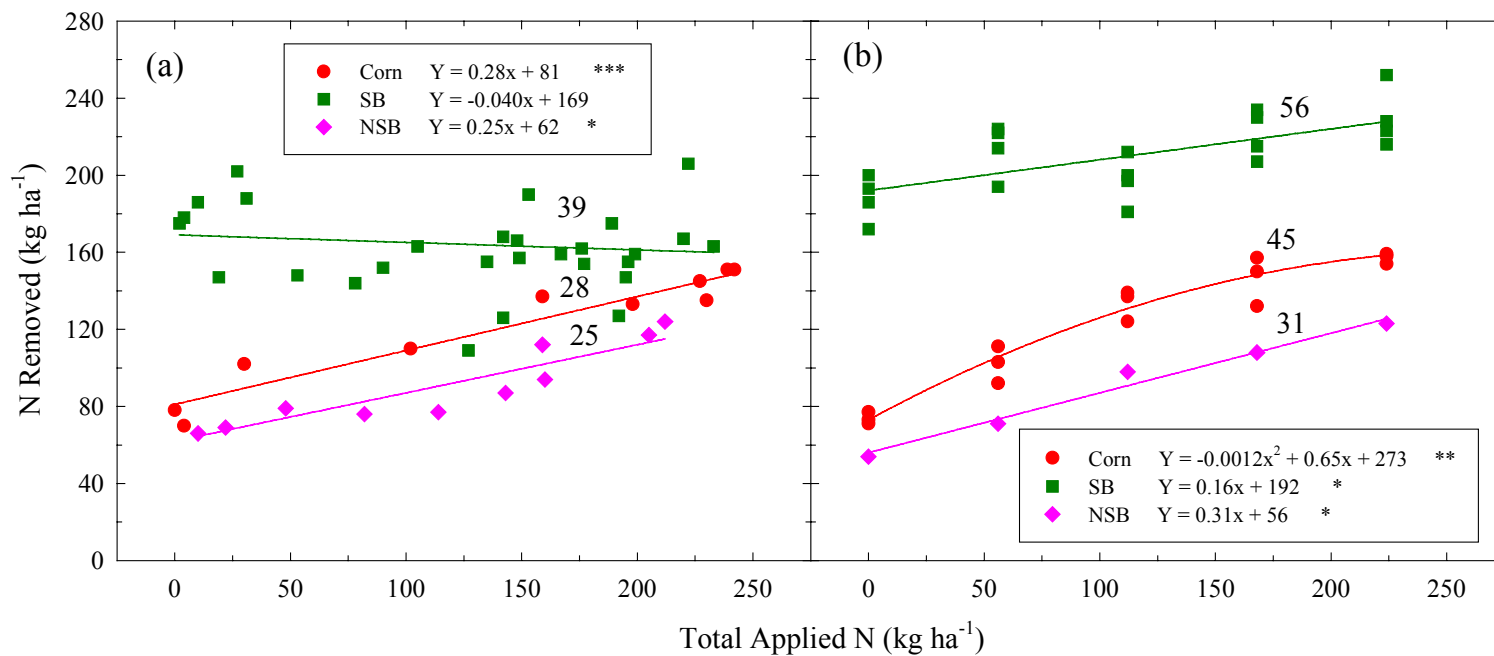


Fig. 3.22. Grain N removal by corn, soybean (SB), and nonnodulating soybean (NSB) in 2000 from SLL additions in (a) Section 2 and (b)  $\text{NH}_4\text{NO}_3$  applications in Section 3. Numbers on the graph are the NUE at an application rate of  $168 \text{ kg N ha}^{-1}$ . \*\*\*, \*\*, \* indicate slopes significant at the 0.001, 0.01, and 0.05 probability levels respectively.



### PAN Determination

Based on corn and nonnodulating soybean yield responses to applied N from SLL and  $\text{NH}_4\text{NO}_3$  in 2000, subtracting only N losses during irrigation from SLL additions underestimates the amount of N available to the crop. In 2000, the average N efficiency of SLL relative to  $\text{NH}_4\text{NO}_3$  was 74 and 73% for corn in Section 1 and 2 respectively. For the nonnodulating soybean in 2000, the N efficiency of SLL relative to  $\text{NH}_4\text{NO}_3$  was 67% in Section 1. In Section 2, yield increases of nonnodulating soybean were not significantly different from N additions of either SLL or  $\text{NH}_4\text{NO}_3$ . When comparing SLL to fertilizer at application rates  $>168 \text{ kg N ha}^{-1}$ , SLL was at least 70% as effective as  $\text{NH}_4\text{NO}_3$  at increasing the amount of grain N removed by corn and nonnodulating soybean in 2000 (Table 3.2). Overall, the efficiencies were higher for the nonnodulating soybean than corn suggesting better N utilization by the nonnodulating soybean. However, corn removed more N through grain production than did the nonnodulating soybean.

Based on the N efficiencies listed in Table 3.2 and the ones recorded for the yield responses to SLL additions in 2000, SLL appeared to be about 70% as effective as  $\text{NH}_4\text{NO}_3$  after accounting for volatilization losses during irrigation. To determine PAN of a SLL sample taken from the lagoon, volatilization losses during irrigation must be considered. Estimated volatilization losses during sprinkler irrigation ranged from 8 to 22% of the pumped SLL for both years (Table 2.3). Assuming 22% N loss during sprinkler irrigation and 70% N availability of SLL after irrigation, the fraction of N available from a lagoon sample would be  $\approx 0.55$  as calculated by  $(1.0 - 0.22) * 0.7$ . The N available fraction of 0.55 is close to the N availability coefficient of 0.5

recommended by the North Carolina Cooperative Extension Service (NCCES, 1990). On the other hand, an N availability fraction of 0.64 from a lagoon sample is obtained assuming only 8% N losses during irrigation. While applied SLL may be >70% as efficient as  $\text{NH}_4\text{NO}_3$  for plant N utilization, determining PAN from SLL sampled from the lagoon is difficult because of N losses during irrigation.

Table 3.2. Nitrogen equivalency of SLL applied by irrigation as compared to  $\text{NH}_4\text{NO}_3$ .

| Crop | Section <sup>†</sup> | Grain N<br>Removed <sup>‡</sup> | $\text{NH}_4\text{NO}_3$<br>Applied<br>kg N ha <sup>-1</sup> | SLL Equivalence to<br>$\text{NH}_4\text{NO}_3$ |            |
|------|----------------------|---------------------------------|--|--|------------|
|      |                      |                                 |  | Amount <sup>§</sup>                            | Percentage |
|      |                      | -----                           | -----  | -----  | %          |
| Corn | 1                    | 106                             | 56   | 149  | 38         |
|      |                      | 131                             | 112  | 216  | 52         |
|      |                      | 148                             | 168  | 262  | 64         |
|      |                      | 158                             | 224  | 289  | 78         |
| Corn | 2                    | 106                             | 56   | 89   | 63         |
|      |                      | 131                             | 112  | 178  | 63         |
|      |                      | 148                             | 168  | 239  | 70         |
|      |                      | 158                             | 224  | 275  | 81         |
| NSB  | 1                    | 73                              | 56   | 74   | 76         |
|      |                      | 91                              | 112  | 152  | 74         |
|      |                      | 108                             | 168  | 226  | 74         |
|      |                      | 125                             | 224  | 300  | 75         |
| NSB  | 2                    | 73                              | 56   | 44   | 127        |
|      |                      | 91                              | 112  | 116  | 96         |
|      |                      | 108                             | 168  | 184  | 91         |
|      |                      | 125                             | 224  | 252  | 89         |

<sup>†</sup>Section 1 received SLL only and Section 2 received SLL and water.

<sup>‡</sup>Grain N removed based on the crop responses to  $\text{NH}_4\text{NO}_3$  (Fig. 3.21).

<sup>§</sup>Calculated from grain N removed by crop in responses to SLL additions (Fig. 3.21 and 3.22). Applied N from SLL is the N amount after application, thus accounting only for N losses during irrigation.

## CONCLUSIONS

Both corn and nonnodulating soybean responded positively to N additions from either SLL or  $\text{NH}_4\text{NO}_3$  in 2000. Corn and nodulating soybean response to N additions in 1999 was limited due to amounts of residual soil N released during the growing season. Based on corn and nonnodulating soybean response in 2000, SLL after irrigation was about 70% as effective as  $\text{NH}_4\text{NO}_3$  for plant N utilization. Assuming 20% volatilization losses during irrigation, N availability of SLL sampled from the lagoon would decrease to 56%. This is close to the N availability coefficient of 0.5 used today in North Carolina to determine PAN for SLL to be applied by irrigation (NCCES, 1990). Depending on N losses during irrigation, PAN calculations based on the 0.5 coefficient could lead to over- or under-application of SLL for crop production. Swine lagoon liquid applications to cropland based on N concentrations measured from catch cans after irrigation would increase the accuracy in predicting PAN.

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## **CHAPTER 4**

### **THE SENSITIVITY OF SOYBEAN NODULATION AND SYMBIOTIC N<sub>2</sub> FIXATION TO NITROGEN FROM APPLIED SWINE LAGOON LIQUID**

#### **ABSTRACT**

Soybean [*Glycine max* (L.) Merr.] is a leguminous crop that has the potential to fix atmospheric N<sub>2</sub>. Generally, symbiotic N<sub>2</sub> fixation decreases when excess inorganic N is available in the soil. Nodule mass and nitrogenase activity as determined by the acetylene reduction method were used to measure the effect of applied N from swine (*Sus scrofa domestica*) lagoon liquid compared to NH<sub>4</sub>NO<sub>3</sub> on symbiotic N<sub>2</sub> fixation. Both nodule mass and nitrogenase activity were reduced as applied N from either swine lagoon liquid (SLL) or NH<sub>4</sub>NO<sub>3</sub> increased. No significant difference was found between the two N sources in reducing potential N<sub>2</sub> fixation. Symbiotic N<sub>2</sub> fixation was reduced by 60% at an N rate of 175 kg ha<sup>-1</sup> for both SLL and NH<sub>4</sub>NO<sub>3</sub>. Since the acetylene reduction method was used only at the R3 growth stage, no definitive measurement of the amount of N<sub>2</sub> fixed over the growing season can be made. However, the decrease in nodule mass and nitrogenase activity with increases in applied N from either SLL or NH<sub>4</sub>NO<sub>3</sub> proves that potential N<sub>2</sub> fixation was significantly reduced.

## INTRODUCTION

Soybean is a leguminous crop that produces grain with a high N concentration (6 to 8% N) as compared to corn (approximately 1.3% N). For North Carolina, the state average soybean yield is 2015 kg ha<sup>-1</sup> and 6290 kg ha<sup>-1</sup> for dryland corn. With this harvested yield, a soybean crop would remove about 141 kg N ha<sup>-1</sup> and a corn crop would remove about 82 kg N ha<sup>-1</sup>. By harvesting the grain, the soybean crop removes almost twice the N amount as compared with corn. Depending on N<sub>2</sub> fixation inhibition from available inorganic soil N, soybean may potentially serve as a receiver crop for the N in SLL. The effectiveness of using soybean as a receiver crop for SLL depends on the inhibition of N<sub>2</sub> fixation and the plant's assimilation of the available inorganic N from the SLL.

Typically, no N fertilizer is added to soybean because they are able to fix N<sub>2</sub> through a symbiotic relationship with a group of soil bacteria collectively known as rhizobia. The rhizobia are free living, motile chemo-heterotrophic bacteria. Once the rhizobia find a suitable host, they attach to the root hairs, and enter the root through an infection thread. As the infection thread penetrates the root cells, rhizobia multiply within the thread and cortex cells within the root begin to divide. The divisions of the cortex cells cause the nodule to form. Once the rhizobia are released into the cortical cells, the rhizobia change to form bacterioids. The bacterioids produce an enzyme complex called nitrogenase. Nitrogenase is responsible for the reduction of N<sub>2</sub> to NH<sub>3</sub> in the nodule. The plant supplies the rhizobia with shelter and C, energy, while in turn the rhizobia provide NH<sub>3</sub> that the plant utilizes as an N source.

Generally, the soybean plant receives about 50 to 80% of its N requirement from N<sub>2</sub> fixation (Israel and Burton, 1997; George et al., 1993; Kohl et al., 1980; Bhangoo and Albritton, 1976; Weber, 1966). The amount of N<sub>2</sub> fixed can be <50% in the presence of significant levels of inorganic N. Since the 1930s, the influence of soil or added available inorganic N on N<sub>2</sub> fixation has been studied (Allos and Bartholomew, 1959). In most cases, it is reported that supplemental inorganic N reduces N<sub>2</sub> fixation. Allos and Bartholomew (1959) reported that when inorganic N is applied in excess of plant requirement, N<sub>2</sub> fixation in several different legumes was suppressed. In some cases, the increase in growth resulting from N fertilization promoted increases in N<sub>2</sub> fixation. Kohl et al. (1980) determined that total plant N coming from N<sub>2</sub> fixation in greenhouse-grown soybean at the R8 stage decreased from 87 to 0% as N applications increased from 0 to 150 mg NO<sub>3</sub>-N kg<sup>-1</sup> soil. Bhangoo and Albritton (1976) found a strong inverse linear correlation between N<sub>2</sub> fixed and N fertilizer applied to soybean. At the 56 kg N ha<sup>-1</sup> application rate, the amount of N<sub>2</sub> fixed by soybean was not significantly different when compared with the unfertilized control. However when application rates exceeded 224 kg N ha<sup>-1</sup>, the N amount fixed decreased to near zero. Depending on available soil N, they determined that fertilizer N could be added up to a rate of 112 kg N ha<sup>-1</sup> for minimum inhibition of N<sub>2</sub> fixation and maximum utilization of the fixed N. Weber (1966) found that symbiotic N<sub>2</sub> fixation in soybean depended largely on available soil N and water. When moisture was adequate, the amount of fixation decreased rapidly with increases in fertilizer N. Symbiotic N<sub>2</sub> fixation was also reduced when moisture was limiting. Weber also reported that nodule number, size, and mass decreased with increases in applied N from 0 to 150 kg ha<sup>-1</sup>.



In studies evaluating  $N_2$  fixation with SLL applications to soybean, the results have been mixed. Using both nodulating and nonnodulating soybean, Israel and Mikkelsen (1998) found that SLL applied at the rate of  $180 \text{ kg N ha}^{-1}$  (plant-available nitrogen, PAN) reduced both nodule mass and nitrogenase activity by 50%. However at a similar  $\text{NH}_4\text{NO}_3$  rate, nitrogenase activity was reduced by 90% and nodule mass by 80%. Therefore,  $N_2$  fixation was more sensitive to applied N from the fertilizer than the SLL. The N recovery efficiency of applied N was about 30% up to the  $278 \text{ kg N ha}^{-1}$  application rate for the nodulating soybean. For the nonnodulated soybean, the N recovery efficiencies for the SLL ranged from 68 to 45% as N rates increased from 112 to  $244 \text{ kg ha}^{-1}$  respectively. Also, higher soil  $\text{NO}_3\text{-N}$  concentrations were found under the nodulated soybean than the nonnodulating isoline. These findings suggest that  $N_2$  fixation is not totally inhibited when the amount of SLL applied does not exceed the agronomic N rate.

Schmidt et al. (2000) evaluated soybean (nodulating and nonnodulating) as an alternative receiver crop to corn for liquid swine manure applications. The liquid swine manure was injected into the soil and the available N was calculated to be 65% of total N applied. No change in biomass N accumulation at the R6 stage or seed yield for the nodulating soybean was noticed with increasing amounts of applied N. Both seed yield and biomass N accumulations increased quadratically up to  $300 \text{ kg N ha}^{-1}$  application rate for the nonnodulating isoline. They also found that post-harvest  $\text{NO}_3\text{-N}$  concentrations in the soil (0 to 120 cm) were similar for the different soybean isolines (nodulated and nonnodulated) with increases in N applied. When N application ( $260$  to  $500 \text{ kg N ha}^{-1}$ ) exceeded the crop requirement,  $\text{NO}_3\text{-N}$  concentrations ranged between

80 to 158 kg N ha<sup>-1</sup> in the upper 120 cm of soil after grain harvest. Nitrogen application rates <260 kg N ha<sup>-1</sup> resulted in soil NO<sub>3</sub>-N concentrations <70 kg N ha<sup>-1</sup>. While no direct measurement of N<sub>2</sub> fixation was made, comparisons based on seed yields, biomass N accumulations, and post-harvest soil NO<sub>3</sub>-N concentrations between the two soybean isolines suggested that N<sub>2</sub> fixation was significantly inhibited. They concluded that soybean could be used as a receiver crop in an environmentally sound manner as long as the applied available N rates are equal to or less than the N accumulated in the crop.

The N difference, isotope tracer, and acetylene reduction methods are commonly used to measure symbiotic N<sub>2</sub> fixation in soybean. The N difference method incorporates the use of a nonnodulating isoline to measure the available soil N or applied N uptake compared with total N uptake of the nodulating isoline (Kohl et al., 1980; Weber, 1966; Bhangoo and Albritton, 1976). The amount of fixed N is estimated by subtracting the amount of N accumulated in the nonnodulating isoline at zero applied N from the nodulating isoline. Isotope tracer methods involve <sup>15</sup>N techniques such as <sup>15</sup>N enrichment and <sup>15</sup>N natural abundance to measure N use. The <sup>15</sup>N natural abundance method measures symbiotic N<sub>2</sub> fixation by comparing the fraction of atmosphere-derived <sup>15</sup>N to the <sup>15</sup>N derived from the soil (George et al., 1993; Kohl et al., 1980). Crop uptake of <sup>15</sup>N from an added source is referred to as the enrichment or tracer method (Wada et al., 1986; Deibert et al., 1979). This method estimates N<sub>2</sub> fixation by multiplying the fertilizer utilization percent against the difference in <sup>15</sup>N uptake by nodulating and nonnodulating isolines.

Hardy et al. (1968) developed the acetylene reduction method as another way to evaluate symbiotic  $N_2$  fixation. Along with reducing  $N_2$  to  $NH_3$ , nitrogenase is able to reduce other compounds such as acetylene ( $C_2H_2$ ) to ethylene ( $C_2H_4$ ). The amount of  $C_2H_4$  produced reflects the specific activity of nitrogenase at a given time. For  $N_2$  fixation to be estimated by this method, numerous measurements have to be made over the growing season. The acetylene reducing activity can be converted to  $N_2$  fixing activity based on the electrons required for reduction. Two electrons are required for  $C_2H_2$  reduction to  $C_2H_4$  and 6 electrons are required for  $N_2$  reduction to  $NH_3$ . Thus, the potential  $N_2$  fixed would be about one third of the amount of  $C_2H_4$  produced. Due to variability over time and the necessity of using a small sample area, the acetylene reducing method is not the best way to quantify actual  $N_2$  fixation. However, the sensitivity of symbiotic  $N_2$  fixation to increases in available N can easily be assessed using the acetylene reduction method.

The objectives of this research were to (1) determine the impact of N additions from SLL as compared to  $NH_4NO_3$  on soybean nodulation, (2) measure the sensitivity of symbiotic  $N_2$  fixation to N additions from SLL as compared to  $NH_4NO_3$ , and (3) estimate the reduction in symbiotic  $N_2$  fixation in response to N additions.

## MATERIALS AND METHODS

Field research was conducted on the Upper Coastal Plain Research Farm located near Rocky Mount, NC. Details of the field site are listed in Chapter 3. The SLL and water was applied using the line-source technique as described in Chapter 2. Figure 2.2 shows the general experimental layout. Simply, the soybean plot was divided into three sections based on the locations of the line-sources. Section 1 received only variable rates of SLL. The area between the SLL and water line-sources, Section 2, received variable rates of SLL while maintaining similar levels of water. Section 3 was divided into subplots that received 0, 56, 112, 168, or 224 kg N ha<sup>-1</sup> of NH<sub>4</sub>NO<sub>3</sub> and variable water rates. In order to avoid complications with the different treatments, the same design was followed both years. In 2000, four rows of a nonnodulating soybean isoline, Lee (D68-0102), were included within the soybean plot.

Soybean was planted in 0.9 m rows and cultivated once during the growing season. In 1999, Pioneer 95B71 soybean was planted on 24 May. In 2000, Asgrow 6101RR soybean was planted on 12 May and the nonnodulating soybean isoline, Lee (D68-0102), was hand planted on 15 May. Since only corn had been planted in the field prior to 1999, soybean seeds were inoculated with rhizobia before planting in 1999. Plant populations were approximately 210,000 ha<sup>-1</sup> in 1999 and 280,000 ha<sup>-1</sup> in 2000. The Research Station staff handled field preparation, planting and weed control for both years. The total amount of N applied was based on N contents measured in catch cans after irrigation (see Chapter 2 for details). The five N fertilizer rates were applied in two applications early in the growing season; broadcasted in 1999 and banded in 2000.

The influence of SLL on N<sub>2</sub> fixation by soybean was measured by the acetylene reduction assay procedure (Hardy et al., 1968) at early pod set (R3 stage). Soybeans were sampled along 3 transects at 3-m intervals for the SLL treatments. For comparisons, only four samples corresponding to different amounts of water applied were taken for each of the fertilizer treatments. After removing the aboveground plant vegetation for a 0.3 m section, the roots were excavated carefully and the loose soil was removed from the roots. This was done at each catch can location within 3 transects. The roots were placed in a 1-L jar and sealed. Acetylene (10% by volume) was added to each jar by removing 100 mL of the air from the jar and then adding 100 mL of C<sub>2</sub>H<sub>2</sub>. The roots were incubated at room temperature for approximately 20 minutes while periodically mixing the air volume within the jar. After incubating for 20 minutes, two 5 mL gas samples were taken from the jar. Following the assay, the nodules were removed from the roots and weighed fresh and after drying in the oven. Ethylene in the gas samples were analyzed with a gas chromatograph equipped with a porapak N column and a flame ionization detector.

## RESULTS AND DISCUSSION

### Nodule Mass

Nodule fresh weight significantly ( $p < 0.05$ ) decreased with increases in applied N from either SLL or  $\text{NH}_4\text{NO}_3$  (Fig. 4.1 and 4.2). The intercepts for nodule mass response to SLL additions in Section 1 and 2 were significantly different for each year while the slopes were similar except for Section 1. Since irrigation depth increased with N additions, it was not possible to test for irrigation effects on nodule mass in Section 1. Irrigation depths did not significantly influence nodule mass in Section 2 because water depths were similar for increasing N rates from SLL. Also, the decrease in nodule mass with N additions was not significantly different between the fertilizer and SLL treatments within each year except for Section 1 in 1999. The influence of  $\text{NH}_4\text{NO}_3$  additions on nodule mass was similar for both years. However, nodule mass was more variable in 2000 when fertilized with  $\text{NH}_4\text{NO}_3$ . Except for the unfertilized control, nodule mass was higher for each fertilizer N rate as irrigation depth increased in 2000 (Fig. 4.3). Nodule mass within each fertilizer rate was not affected by irrigation depth in 1999.

The differences in intercepts between years suggest a change in some parameter other than total applied N. One possibility is the influence of residual soil N. In 1999, it was estimated that 101 to 116 kg N ha<sup>-1</sup> was mineralized from the soil (Chapter 5). For 2000, 56 to 81 kg N ha<sup>-1</sup> was mineralized from the soil. In previous years, SLL was applied at agronomic rates to corn in this same field. Thus, this may explain the high levels of residual soil N.

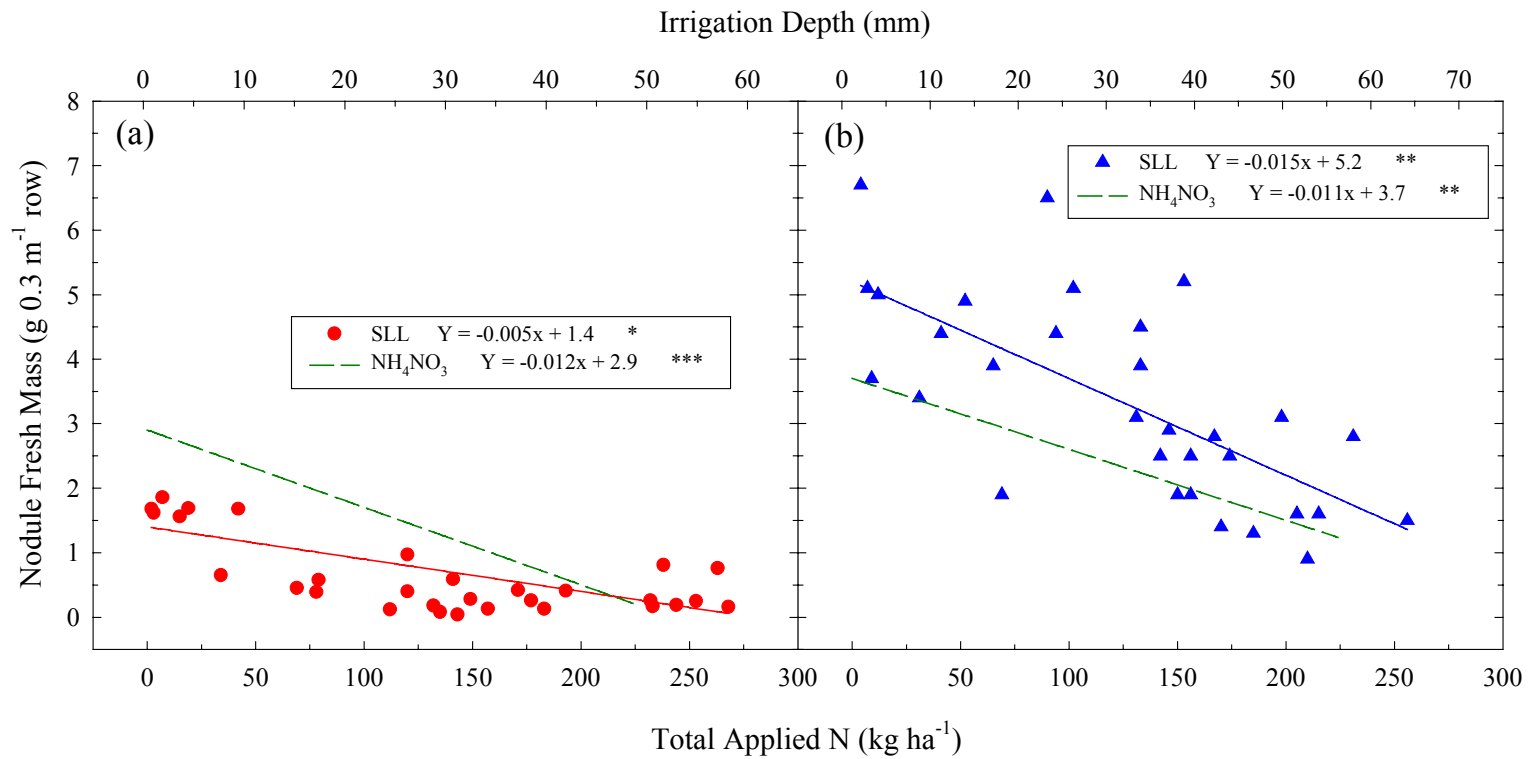


Fig. 4.1. Fresh nodule mass from soybean roots in (a) 1999 and (b) 2000 as influenced by SLL additions in Section 1 and fertilizer applications in Section 3. Irrigation depth pertains only to SLL additions. \*, \*\*, \*\*\* indicate slopes significant at the 0.05, 0.01, and 0.001 probability levels respectively.

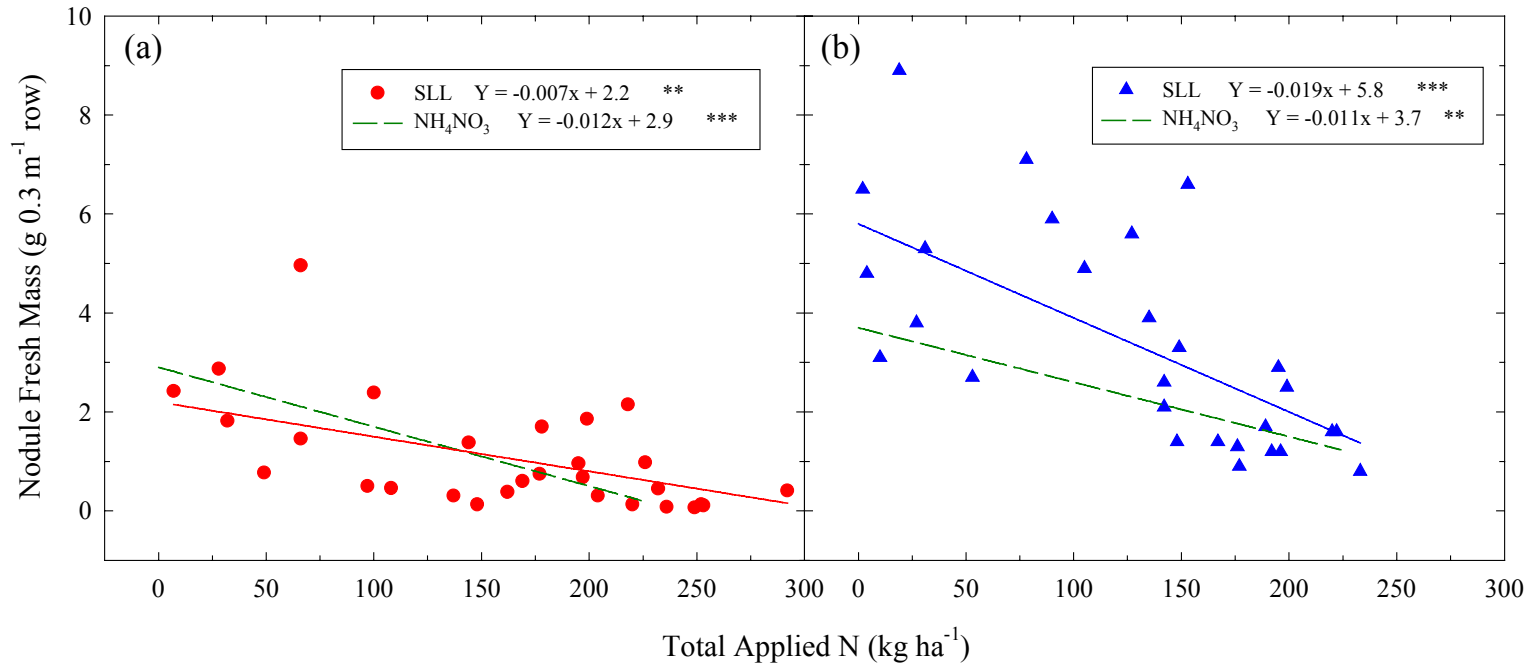


Fig. 4.2. Fresh nodule mass from soybean roots in (a) 1999 and (b) 2000 as influenced by SLL additions in Section 2 and fertilizer applications in Section 3. Irrigation depths ranged from 40 to 80 mm in Section 2 for both years. \*\*, \*\*\* indicate slopes significant at the 0.01 and 0.001 probability levels respectively.



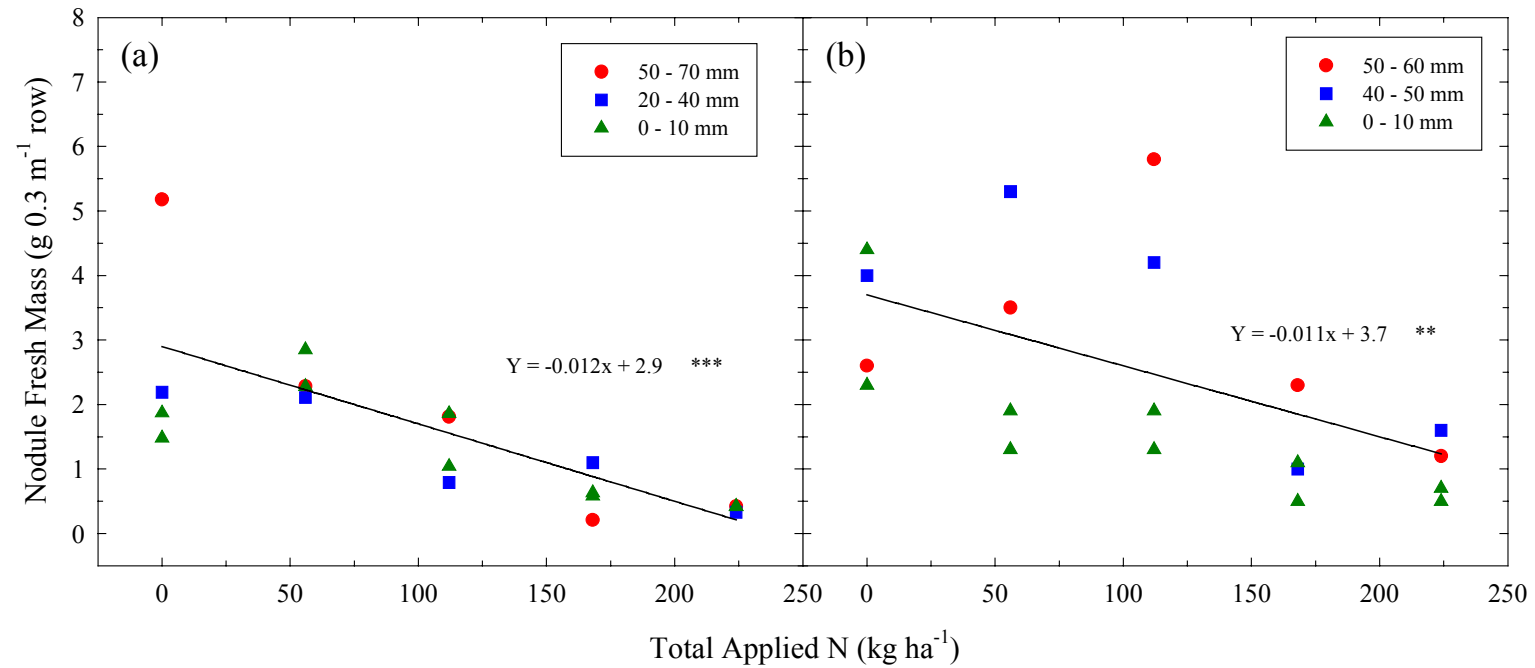


Fig. 4.3. Influence of increasing  $\text{NH}_4\text{NO}_3$  rates and water irrigation depths on fresh nodule mass in (a) 1999 and (b) 2000. With only 4 observations taken for each N rate, a complete irrigation depth range from 0 to 70 mm was not obtained. \*\*, \*\*\* indicate slopes significant at the 0.01 and 0.001 probability levels respectively.

Another possible reason for the difference in intercepts between years may have been due to a low initial population of rhizobia in the soil in 1999. Since mainly corn had been grown in that field, it is reasonable to assume that the rhizobia population would have been lower in 1999 than 2000. The population should have been higher in 2000 because soybeans were grown in 1999. However, the rhizobia population should have been high enough in 1999, since the soybean seeds were inoculated with rhizobia at planting.

Nodule mass was reduced more by  $\text{NH}_4\text{NO}_3$  than SLL in 2000 as shown by the differences in the slope of the regression line (Fig. 4.1 and 4.2). The differences in slope suggest that the  $\text{NH}_4\text{NO}_3$  was more effective in suppressing nodulation at similar N rates than was SLL. However, the difference between  $\text{NH}_4\text{NO}_3$  and SLL could also suggest that the calculated applied N from SLL did not accurately reflect the PAN. By comparing the slopes of the regression lines for fertilizer and SLL in 2000, the fertilizer N to SLL N ratio was 0.73:1 and 0.58:1 for Sections 1 and 2 respectively. Therefore, SLL was about 70 to 60% as effective as  $\text{NH}_4\text{NO}_3$  for reducing nodule mass.

### **Sensitivity of Symbiotic $\text{N}_2$ Fixation to SLL Additions**

Suppression of symbiotic  $\text{N}_2$  fixation following N fertilization was also noticed when nitrogenase activity was measured by the acetylene reduction method (Fig. 4.4, 4.5, and 4.6). Nitrogenase activity was reduced at the R3 stage from additions of SLL or  $\text{NH}_4\text{NO}_3$ . As noticed with nodule weights, the intercepts were significantly different between years within a section. The slopes of the SLL regression lines were not significantly different from the fertilizer treatment except for Section 1 in 1999. The

difference between the fertilizer slope and SLL slope from Section 1 may be due to the increasing irrigation depths that correspond to N additions. As with nodule weight in 2000, irrigation depth significantly influenced  $C_2H_2$  reductions within the fertilizer treatments in Section 3 (Fig. 4.6). In all cases but one, the slopes were significant for either nodule mass or  $C_2H_2$  reduction depending on the amount of N applied. However, nodule mass and  $C_2H_2$  reduction measurements were highly variable within each section. This variability may be a reflection of the small sample area (0.3 m of row). Another potential source of variability is the method of N application. In 2000,  $NH_4NO_3$  was banded beside the soybean whereas the SLL was applied by irrigation over the entire area. By banding  $NH_4NO_3$ , the N was placed close to the plant.

Since fresh nodule mass and nitrogenase activity responded similarly to N additions, a positive relationship between nodule mass and nitrogenase activity was verified (Fig. 4.7). Nodules on the roots would be expected if symbiotic  $N_2$  fixation was occurring. While all nodules may not be active, increases in nodule mass should also result in higher nitrogenase activity. The relationship between nodule mass and nitrogenase activity varied significantly between 1999 and 2000. With the exception of 2000, the sections (1, 2, and 3) did not differ in the amount of  $C_2H_4$  evolved based on nodule mass. Therefore, the rate of  $C_2H_4$  evolution in relation to nodule mass was plotted on a yearly basis using the measurements from all sections (Fig. 4.7). Increases in the rate of  $C_2H_4$  evolution were strongly correlated to nodule mass.

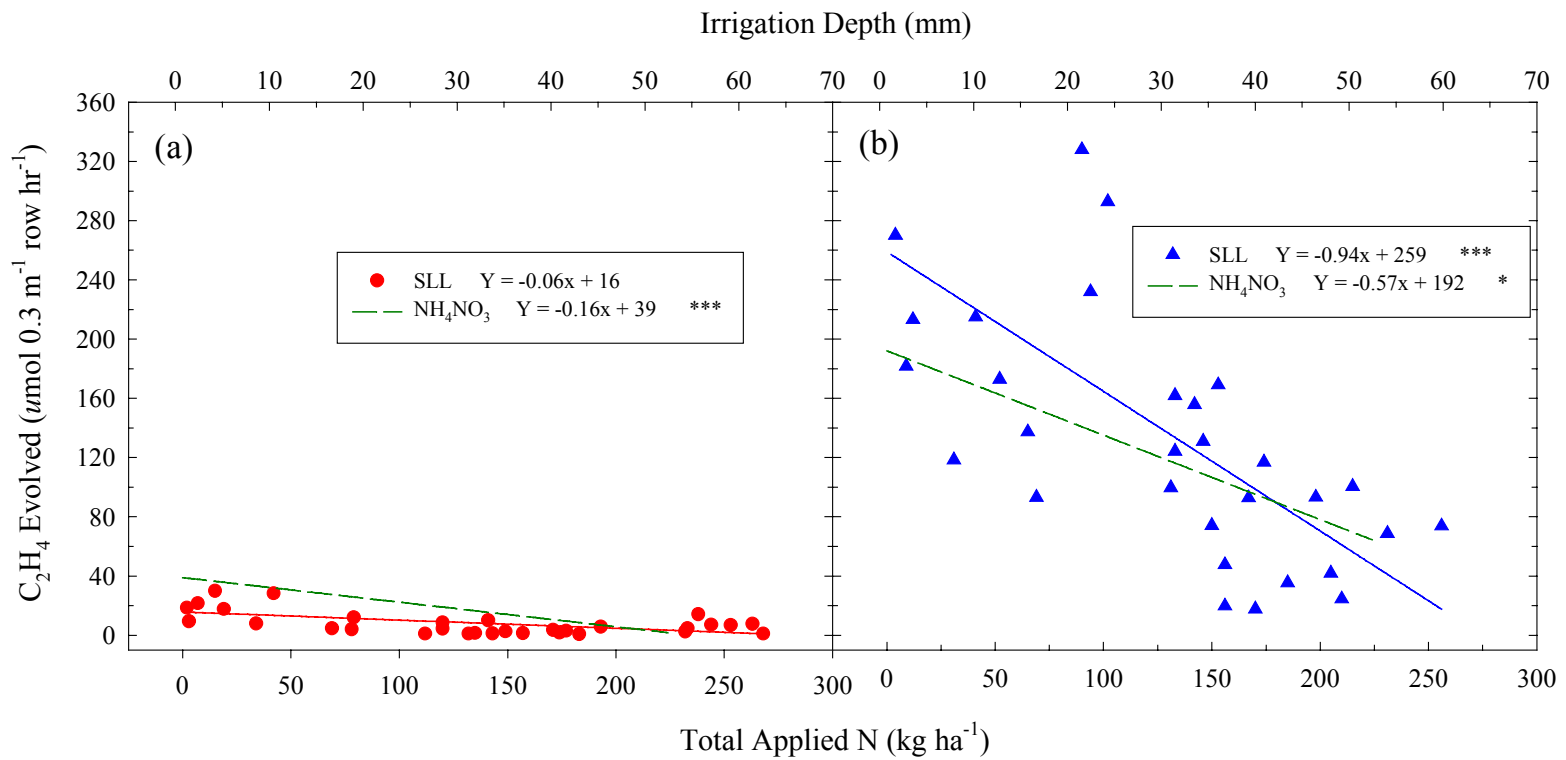


Fig. 4.4. Acetylene reduction activity of soybean nodules in (a) 1999 and (b) 2000 as affected by SLL additions in Section 1 compared to fertilizer applications in Section 3. Irrigation depths only pertain SLL additions. \*, \*\*\* indicate slopes significant at the 0.05 and 0.001 probability levels respectively.

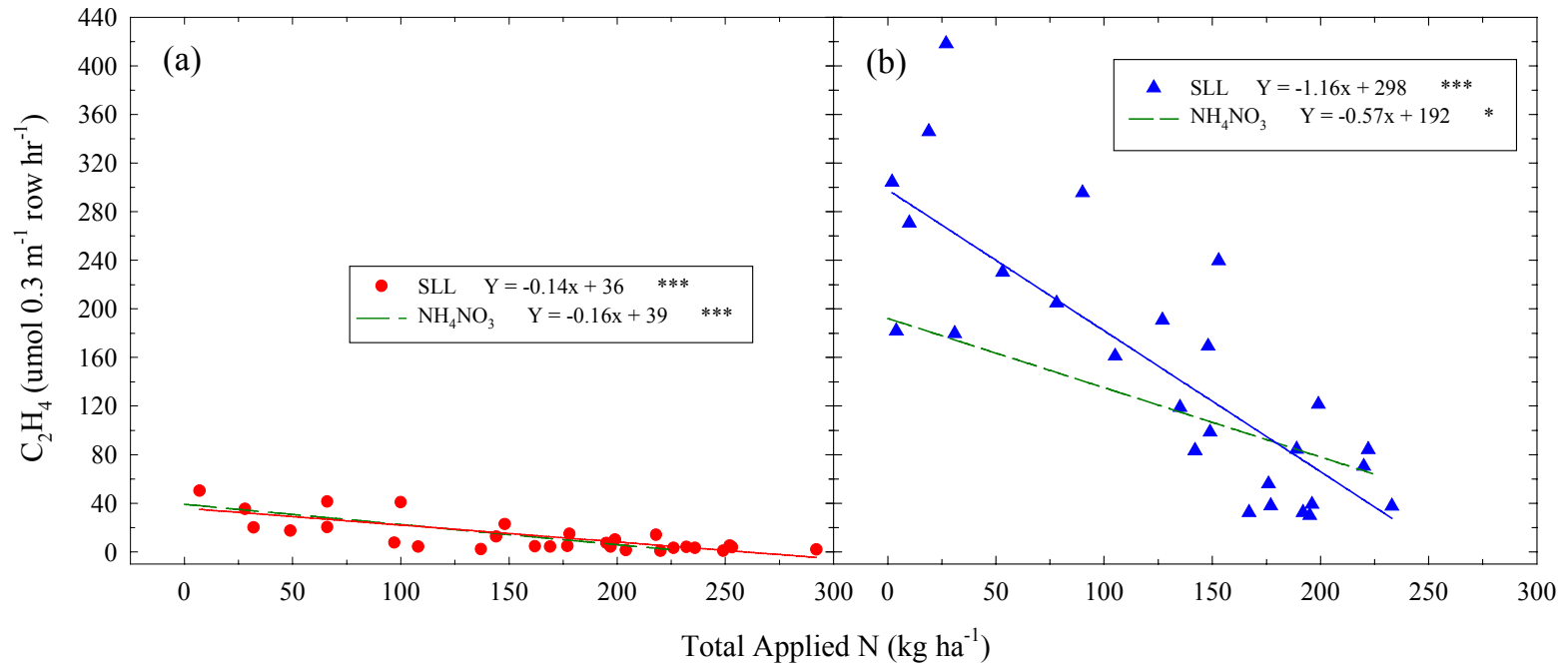


Fig. 4.5. Acetylene reduction activity of soybean nodules in (a) 1999 and (b) 2000 as affected by SLL additions in Section 2 compared to fertilizer applications in Section 3. Irrigation depths ranged from 40 to 80 mm in Section 2 for both years. \*, \*\*\* indicate slopes significant at the 0.05 and 0.001 probability levels respectively.

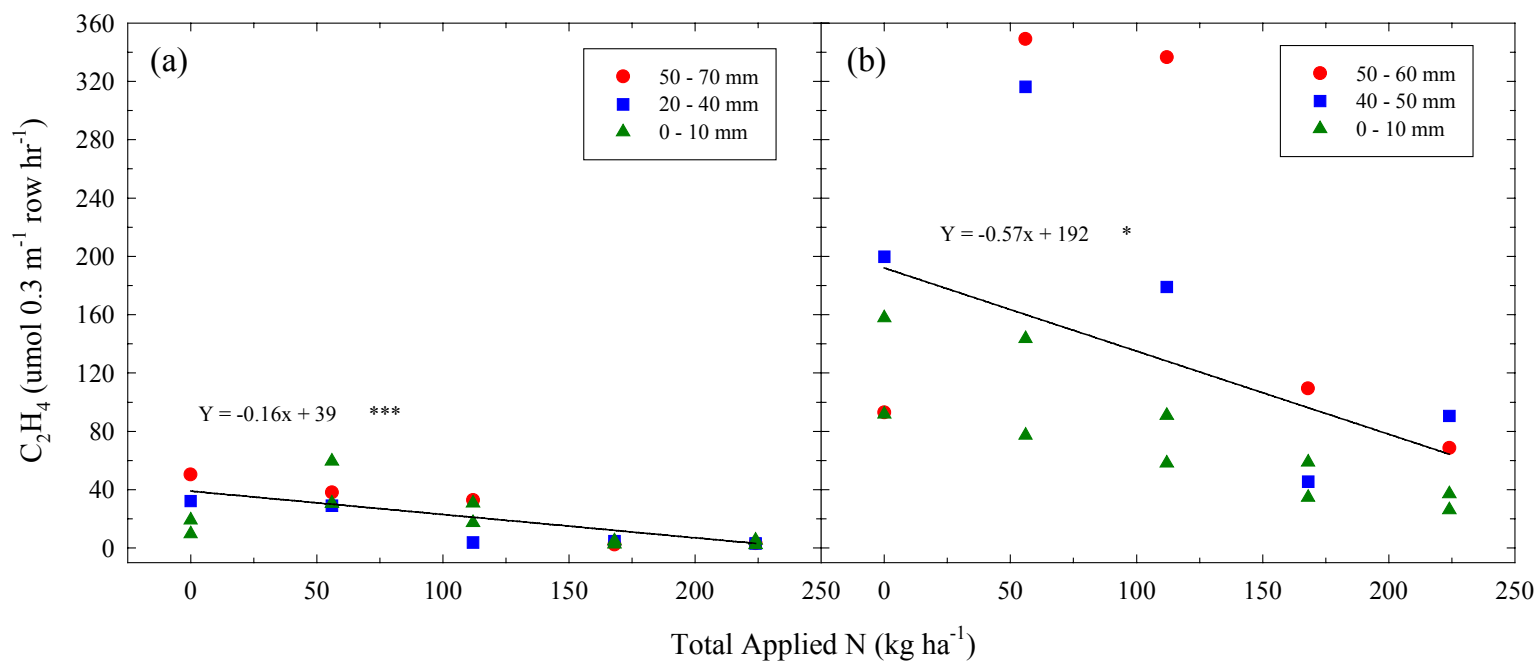


Fig. 4.6. Acetylene reduction activity of soybean nodules in (a) 1999 and (b) 2000 as affected by increasing  $\text{NH}_4\text{NO}_3$  rates and water irrigation depths. With only 4 observations taken for each N rate, a complete irrigation depth range from 0 to 70 mm was not obtained. \*, \*\*\* indicate slopes significant at the 0.05 and 0.001 probability levels respectively.

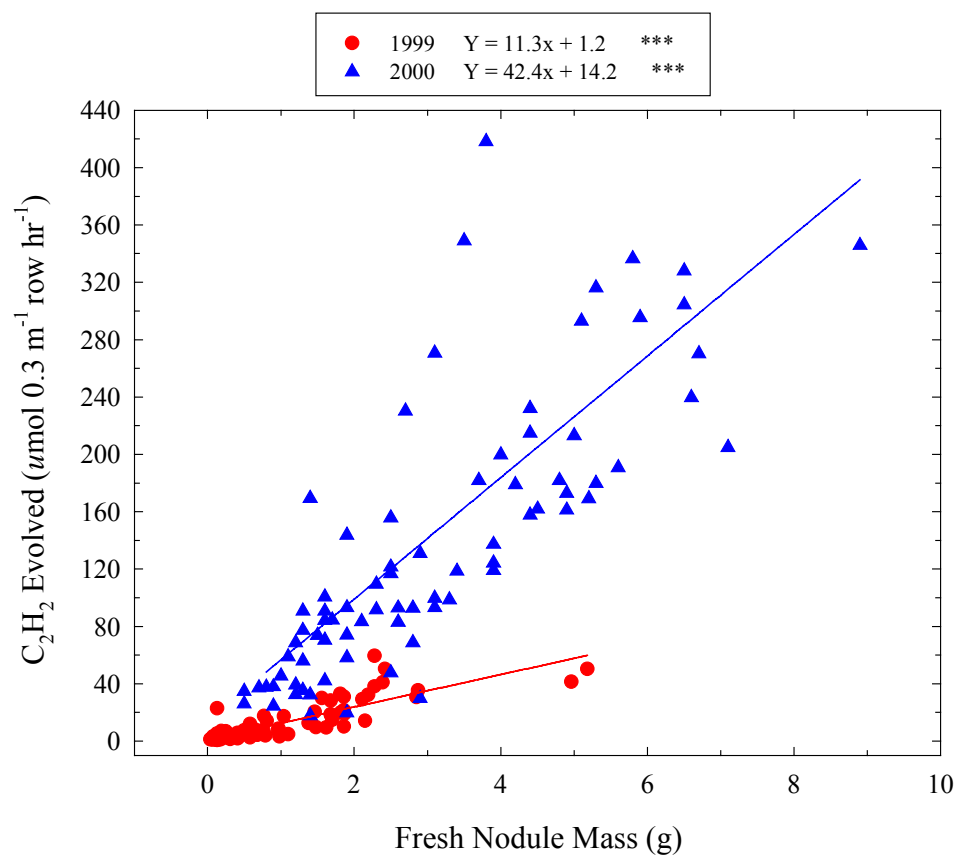


Fig. 4.7. Total acetylene reduction activity of soybean nodules as reflected by nodule mass. \*\*\* indicates slopes significant at the 0.001 probability level.

### Estimation of Reduction in Symbiotic N<sub>2</sub> Fixation

Assuming that N<sub>2</sub> fixation is not inhibited at the applied N rate of 0 kg ha<sup>-1</sup>, data from the C<sub>2</sub>H<sub>2</sub> reduction measurements can be used to estimate the influence of N additions on the potential N<sub>2</sub> fixed. The percent reduction in potential N<sub>2</sub> fixation was calculated by:

$$\% \text{ Red.} = ((C_0 - A_i) / C_0) * 100$$

where

C<sub>0</sub> is the intercept from Fig. 4.4 and 4.5 (μmol 0.3 m<sup>-1</sup> row h<sup>-1</sup>); and

A<sub>i</sub> is the measured C<sub>2</sub>H<sub>4</sub> at the N application rates (μmol 0.3 m<sup>-1</sup> row h<sup>-1</sup>).

The reduction in N<sub>2</sub> fixation increased with N additions from either SLL or NH<sub>4</sub>NO<sub>3</sub> (Fig. 4.8, 4.9, and 4.10). Unlike earlier trends, the increase in N<sub>2</sub> fixation reduction was not significantly different between applied N from either SLL or NH<sub>4</sub>NO<sub>3</sub>. Other than an irrigation effect in 2000, the reduction in N<sub>2</sub> fixation was not significantly affected by sections (1, 2, and 3) or years. The level of inhibition of N<sub>2</sub> fixation from SLL additions in this study was similar to that reported by Israel and Mikkelsen (2001). Using the <sup>15</sup>N natural abundance method, Israel and Mikkelsen (2001) demonstrated that N<sub>2</sub> fixation contributed 27% of the seed N accumulated by nodulated soybean when supplied with 200 kg N ha<sup>-1</sup> from SLL. While the reduction in N<sub>2</sub> fixation from N additions was roughly estimated using C<sub>2</sub>H<sub>2</sub> reduction measurements, the estimated reductions were reasonable since they were similar to other studies that measured symbiotic N<sub>2</sub> fixation.



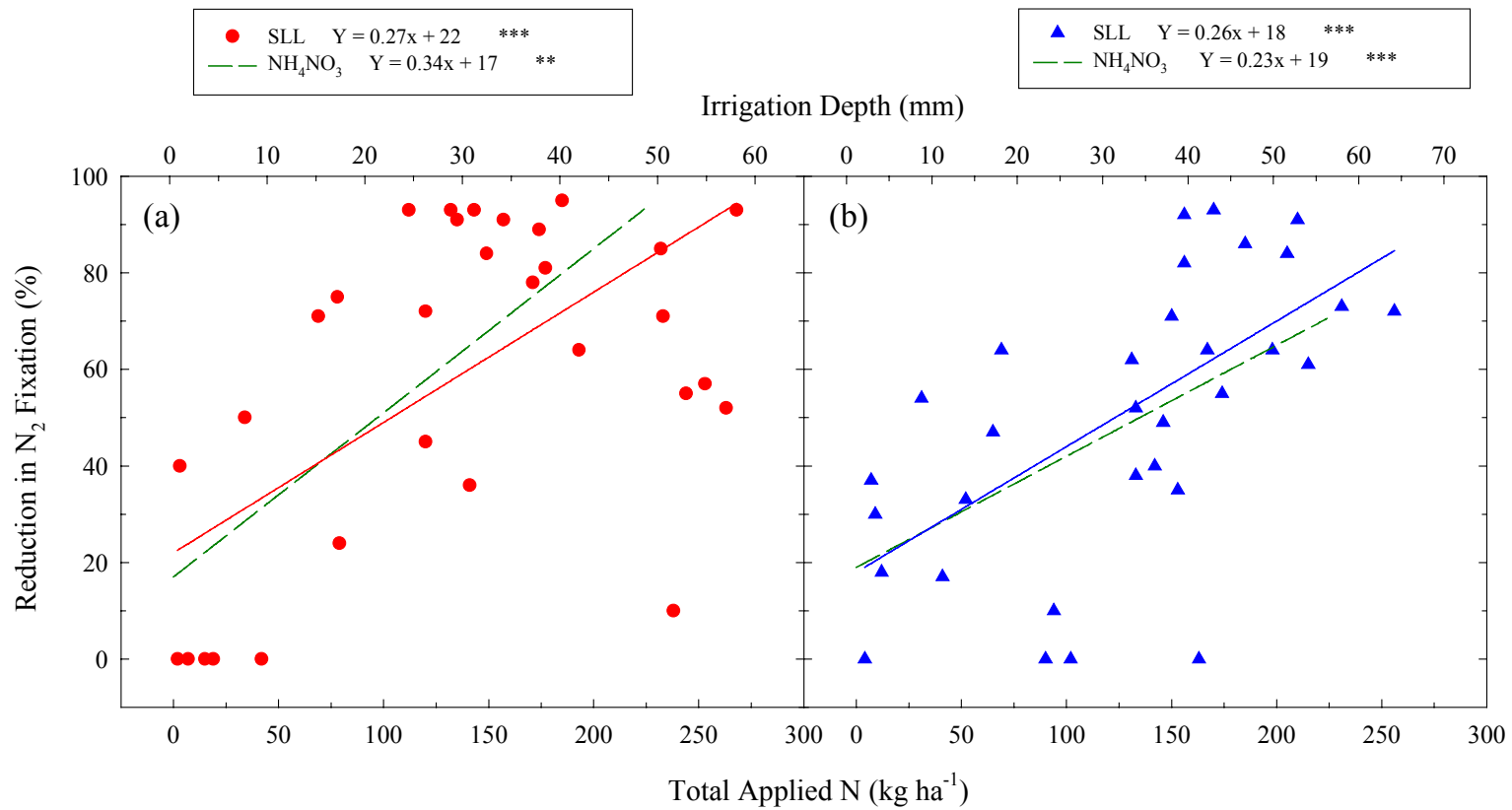


Fig. 4.8. Estimation of  $N_2$  fixation reduction in (a) 1999 and (b) 2000 from additions of SLL in Section 1 compared to fertilizer applications in Section 3. Irrigation depths only pertain SLL additions. \*\*, \*\*\* indicate slopes significant at the 0.01 and 0.001 probability levels respectively.

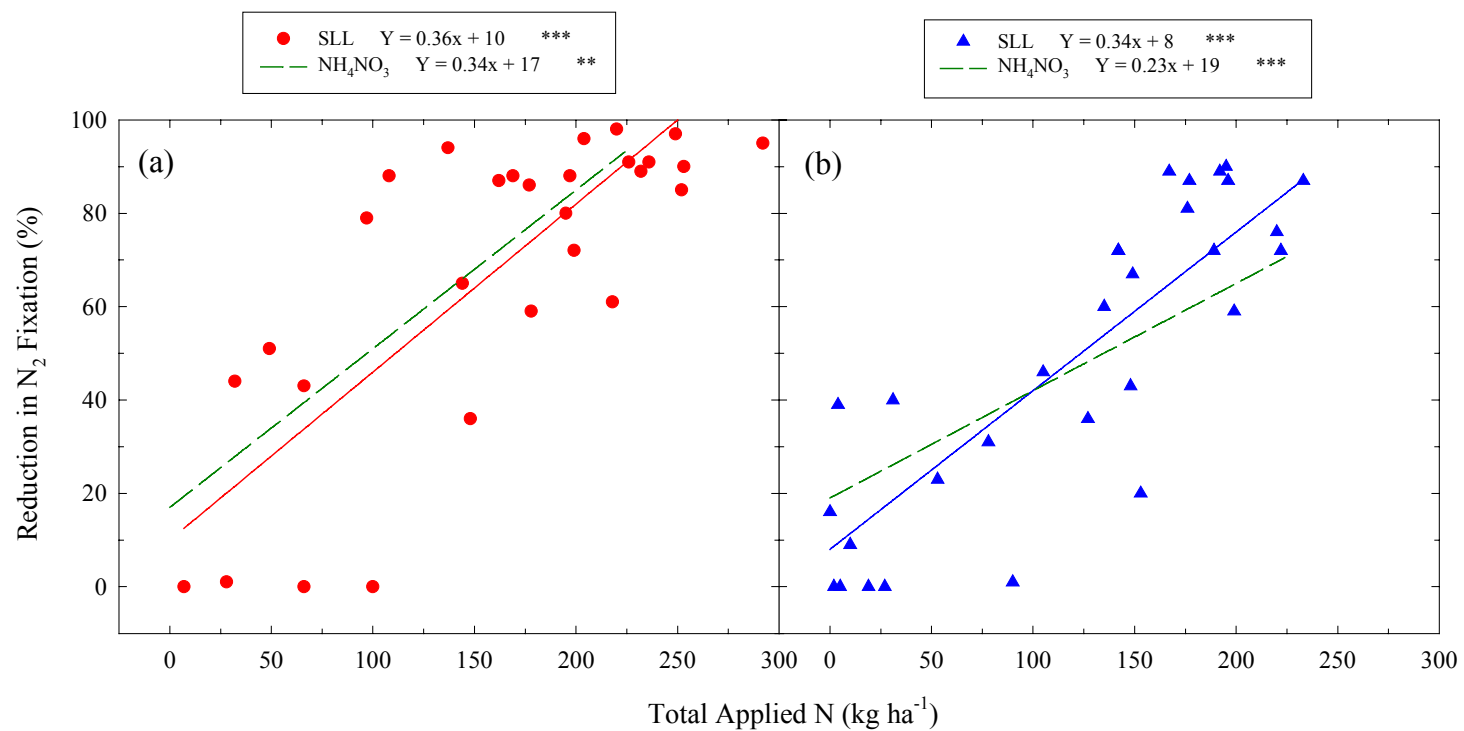


Fig. 4.9. Estimation of  $N_2$  fixation reduction in (a) 1999 and (b) 2000 from additions of SLL in Section 2 compared to fertilizer applications in Section 3. \*\*, \*\*\* indicate slopes significant at the 0.01 and 0.001 probability levels respectively.

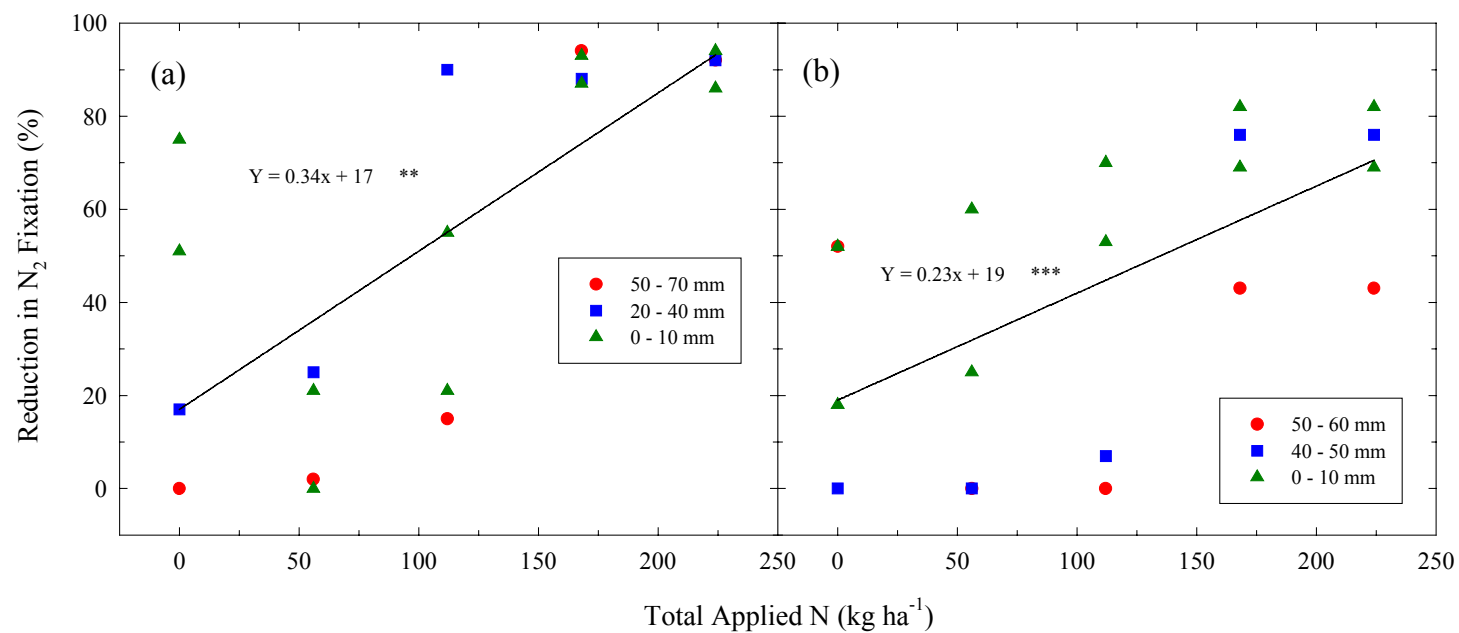


Fig. 4.10. Estimation of N<sub>2</sub> fixation reduction in (a) 1999 and (b) 2000 as affected by increasing NH<sub>4</sub>NO<sub>3</sub> rates and water irrigation depths. With only 4 observations taken for each NH<sub>4</sub>NO<sub>3</sub> rate, a complete irrigation depth range was not obtained. \*\*, \*\*\* indicate slopes significant at the 0.01 and 0.001 probability levels respectively.

## CONCLUSIONS

Additions of N from either SLL or  $\text{NH}_4\text{NO}_3$  reduced potential  $\text{N}_2$  fixation of soybean both years. Reductions in fresh nodule mass and  $\text{C}_2\text{H}_4$  evolved were measured with increasing amounts of N. Potential  $\text{N}_2$  fixation was reduced by 60% at an application rate of approximately  $175 \text{ kg N ha}^{-1}$  in 2000. In no case was  $\text{N}_2$  fixation totally inhibited. Since no accurate measurement of  $\text{N}_2$  fixation was made, the ability of soybean to remove applied N can only be estimated.

Outside of nodule mass, the influence of applied N from either SLL or  $\text{NH}_4\text{NO}_3$  was not significantly different in suppressing  $\text{N}_2$  fixation. Similar to the results reported in Chapter 3, applied SLL by irrigation appears to be about 70% as effective  $\text{NH}_4\text{NO}_3$  for crop utilization based on reductions in nodule mass in 2000. This efficiency is based on total N collected in catch cans, thus accounting for only N losses during irrigation of the SLL.

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## **CHAPTER 5**

### **POTENTIAL ENVIRONMENTAL IMPACTS FROM SWINE LAGOON LIQUID APPLIED TO FIELD CROPS**

#### **ABSTRACT**

Elevated N levels in the surface waters and groundwater has led to evaluations of current agricultural N management practices and their potential impacts on the environment. Applied N from anaerobic swine lagoon liquid (SLL) applied by irrigation to cropland was compared to  $\text{NH}_4\text{NO}_3$  for potential N losses to the environment. The effects of SLL and  $\text{NH}_4\text{NO}_3$  applications to corn (*Zea mays* L.) and soybean (*Glycine max* Merrill) on soil inorganic N concentrations were measured at planting and after harvest. In 2000, a laboratory incubation study of four field soils was conducted to determine the influence of previous SLL applications to corn and soybean on potential N mineralized. Soil inorganic N concentrations generally were higher at the end of the growing season for both corn and soybean in 1999 than 2000 due to the low crop recovery of applied N in 1999. For 2000, soil inorganic N concentrations after harvest were usually higher for both nodulating and nonnodulating soybean than corn at all N rates using either SLL or  $\text{NH}_4\text{NO}_3$ . Based on a first order model describing mineralized N accumulations from the four soils, no significant difference was found between crops and applied SLL on the rate of N mineralized. Appropriate N applications of SLL or  $\text{NH}_4\text{NO}_3$  pose little threat to the environment. However, processes such as mineralization can release N for crop utilization and limit the amount of applied N removed in the grain.

## INTRODUCTION

To utilize plant nutrients and water from anaerobic SLL, application of SLL by irrigation to a growing crop is an acceptable means of treatment and disposal. Nitrogen tends to be the nutrient most limiting for plant growth, therefore SLL applications are generally based on estimated plant-available N (PAN) and the N required to produce optimum crop yields. Unutilized N can potentially impact the environment when N applications are in excess of a crop requirement to produce optimum yields. Nitrogen that is not utilized by the plant may be lost to the environment through runoff, leaching, volatilization, and denitrification. The potential for over-application of N from SLL exists because of the amount of SLL generated in a relatively small geographical area (see Introduction in Chapter 1) and the difficulty in predicting the N accessible by the crop. Other concerns about N-based waste applications are the accumulations of P and heavy metals such as Cu and Zn in the soil (Mikkelsen, 2000a).

Leaching of  $\text{NO}_3\text{-N}$  is a concern because it can decrease groundwater quality particularly for drinking. Due to human health concerns, the US Public Health Service has established a standard of  $10 \text{ mg NO}_3\text{-N L}^{-1}$  as the maximum concentration safe for humans to drink. Causes of elevated groundwater  $\text{NO}_3\text{-N}$  concentrations are known to come from improper use of fertilizer N (inorganic and organic), land applications of excessive rates of municipal and industrial wastewaters, landfills, septic systems, as well as mineralization of soil organic matter. Stone et al. (1995) evaluated the influences of intensive agricultural practices on groundwater quality within a watershed in Duplin County, NC. Of the 21 farms monitored, 5 farms had mean  $\text{NO}_3\text{-N}$  concentrations ranging from 10 to  $18 \text{ mg L}^{-1}$  from the groundwater monitoring wells.

One farm with an undersized SLL spray field consistently had  $\text{NO}_3\text{-N}$  concentrations that exceeded  $50 \text{ mg L}^{-1}$ . This study also looked at over 100 residential drinking wells and found that about 25% exceeded the  $10 \text{ mg L}^{-1}$  threshold. All of the water samples that exceeded the standard were obtained from shallow wells ( $<30 \text{ m}$ ).

Also,  $\text{NO}_3^-$  leaching to the groundwater is a concern because of surface water quality degradation. Nitrogen lost to surface waters through runoff or subsurface water flow can lead to eutrophication. Nutrient enrichment of surface waters is often associated with increased algae growth. Ultimately, the algae dies and decomposes, thereby depleting the dissolved oxygen (hypoxia). Insufficient dissolved oxygen in the water leads to fish kills. Besides episodic fish kills, eutrophication has been receiving much attention because of the impacts on estuaries. The Chesapeake Bay, which is the largest US estuary, has been studied extensively (Boesch et al., 2001). In response to these studies showing increased nutrients levels and declines in certain aquatic vegetation, a Chesapeake Bay Agreement was implemented in 1987 seeking a 40% reduction in N and P loads into the watershed for both point and nonpoint sources. Eastern North Carolina is in a similar situation with recurring and worsening algal blooms and large fish kills within its surface waters (Karr et al., 2001). The Neuse River Basin was declared a nutrient-sensitive watershed in 1993 (Karr et al., 2001). After evaluating 92% of the stream miles, only 22% was found to be fully supporting of their designated uses (e.g., drinking, swimming, and fishing). Agriculture was implicated in affecting 34% of the impaired stream miles. Livestock production, especially swine, in this area is under high scrutiny because of rapid growth in the last decade and land-based waste treatment.



Besides potential odor problems and respiratory irritations,  $\text{NH}_3$  volatilization is a concern because of its role in acidification and eutrophication of natural ecosystems from the redeposition of  $\text{NH}_3$  as  $\text{NH}_4^+$ . Natural ecosystems become N enriched as  $\text{NH}_4^+$  is deposited, while the soil pH decreases over time due to nitrification. Agricultural emissions of  $\text{NH}_3$  have been implicated in forest decline (McLeod et al., 1990; Nihlgard, 1985). Schlesinger and Hartley (1992) estimated that domestic animals contributed 40 to 50% of the total global  $\text{NH}_3$  deposition,  $57 \text{ Tg N yr}^{-1}$  (Tg = terragram,  $10^{12} \text{ g}$ ). In North Carolina, swine production accounts for about 33% of the state's total estimated  $\text{NH}_3\text{-N}$  emissions (Robarge et al., 2001). Of the 33%  $\text{NH}_3\text{-N}$  emissions from swine operations, 95% of the emissions were generated within the Coastal Plain. However, the maximum  $\text{NH}_3$  concentrations (1,244 ppb) measured in emissions from a swine waste lagoon never reached the state's acceptable ambient limit of 3,900 ppb. Paerl (1993) found that surface waters downwind of these areas with high  $\text{NH}_3$  emissions had increased intensities and frequencies of algal blooms. Thus, it appears while the maximum  $\text{NH}_3$  concentrations from a lagoon may be below the state's acceptable ambient limit,  $\text{NH}_3$  emissions are still a potential N source influencing the decline of surface water quality and impacting natural ecosystems.

The production of nitrous oxide ( $\text{N}_2\text{O}$ ) through denitrification and nitrification is a concern because of global warming and ozone layer depletion (Peoples et al., 1995). In the troposphere,  $\text{N}_2\text{O}$  absorbs thermal radiation, thus contributing to greenhouse warming. The ozone layer in the stratosphere serves as a barrier against harmful solar ultraviolet radiation penetrating through the atmosphere to the earth's surface. It has been estimated that agricultural use of fertilizer releases between  $0.2$  and  $2.1 \text{ Tg ha}^{-1}$

N<sub>2</sub>O into the atmosphere annually (Sims, 1995). However, the reported percentages that agricultural fertilizer use contributes to total global N<sub>2</sub>O varies from 3 (Sims, 1995) to 13% (Peoples et al., 1995). Also, these emissions do not include animal wastes added to land as a fertilizer source.

While researchers disagree as to how much agriculture contributes to environmental problems, research has indicated that agriculture is a source of the increased N in the environment. One way to determine the potential environmental impact of using fertilizer N (inorganic or organic) for crop production is to do an N balance. Very simply, any of the applied N (input) not utilized by the crop (output) is potentially lost to the environment through leaching, runoff, volatilization, and denitrification. The objectives of this research were to: (1) measure changes in soil inorganic N as a result of different crops and N application rates from SLL as compared to fertilizer N, (2) determine N potentially available to the crop from mineralization of organic N, and (3) determine potential N lost to the environment from SLL applied by irrigation to different crops as compared to fertilizer N.

## **MATERIALS AND METHODS**

Field research was conducted on the Upper Coastal Plain Research Farm located near Rocky Mount, NC. A description of the soil and research implementation is further covered in the Materials and Methods in Chapter 3. Figure 2.2 shows the field research plot design. Applied N from SLL was measured as the N content of the catch cans (Chapter 2). The fertilizer treatment included application rates of 0, 56, 112, 168,

and 224 kg N ha<sup>-1</sup> of NH<sub>4</sub>NO<sub>3</sub> (see Chapter 3 for further details). In 2000, a nonnodulating soybean isoline, Lee (D68-0102), was included in the field research.

### **Soil Sampling**

Soil samples were taken at the beginning of the growing season and after all the crops had been harvested. In the spring of 1999, soil samples were taken on a 14.6 m (x coordinate) by 24.3 m (y coordinate) grid within each section. For the subsequent sampling periods, soil samples were taken every 3 m along a specific catch can transect for all crops. Soil samples taken in the NH<sub>4</sub>NO<sub>3</sub> treatments (Section 3) were a composite of three sampling points across all irrigation levels for each N rate. The soil was obtained from cores taken by a tractor-mounted hydraulic probe unit sampled to a depth of 0.9 m. At each location, three adjacent cores were taken and separated into three 0.3 m segments starting from the soil surface. The segments from the three cores were placed into separate plastic buckets and mixed. A composite subsample was taken from each bucket and air-dried. The soil samples were ground and passed through a 2-mm mesh screen.

The amount of inorganic N in the soil was determined by extracting 10 g of dried soil in 25 ml of 1M KCl. After shaking for 30 minutes, soil extracts were filtered using Watman # 2 filters. Extracts were frozen until they could be analyzed for N. The concentrations of NO<sub>3</sub>-N and NH<sub>4</sub>-N were determined colorimetrically using a Lachat autoanalyzer (Milwaukee, WI) following the procedures as outlined by Quik Chem Methods 10-107-04-1-A and 10-107-06-2-A (Lachat Instr., 1993) for NO<sub>3</sub>-N and NH<sub>4</sub>-N respectively.

### **Mineralization Study**

During the first week of June 2000, soil was collected from both corn and soybean areas in Section 1 that received the highest and lowest applications of SLL during 1999. The High N Corn and High N Soybean soil samples were obtained from the area that received 119 to 190 kg N ha<sup>-1</sup> and 157 to 268 kg N ha<sup>-1</sup> from applied SLL in Section 1 respectively. The Low N Corn and Low N Soybean soil samples were taken from the area that received 0 to 45 kg N ha<sup>-1</sup> and 0 to 78 kg N ha<sup>-1</sup> in Section 1 respectively. A soil with similar properties and no previous history of N applications was sampled from a nearby pine forest to be used as the control. Soil was collected from the 0 to 0.15 m and 0.15 to 0.30 m depths at each location, sieved through 2-mm screen, and mixed in a V-mixer for 30 minutes. After mixing, 100 g of soil was weighed and placed into polyethylene bags. The bags were kept at room temperature (22 – 25°C) in a dark closet. Distilled water was periodically added to maintain a moisture content of approximately 10% dry weight basis. Four replicated sample bags were removed from the closet following 1, 2, 3, 4, 5, 6, 8, 10, 12, 14, and 16 weeks after sampling for analysis of inorganic N. Ten grams of soil from each bag was extracted with 25 ml of 1M KCl, following the same procedure as previously described. The extracts were frozen until they could be analyzed for NO<sub>3</sub>-N and NH<sub>4</sub>-N as described earlier. At the time of extraction, another soil sample (≈10 g) was taken and oven dried at approximately 105°C to determine moisture content.

## Statistical Analysis

The PROC GLM procedure (SAS, 1998) was used to evaluate the linear response of soil inorganic N changes by the end of the growing season to applied N. An ANOVA table was generated to check for the effects of applied N, soil depth, and crops on soil inorganic N concentrations. For the mineralization study, the PROC NLIN procedure was used to fit the data to a first-order accumulation model (Chescheir et al., 1986):

$$N_t = N_0 * (1 - \exp(-k * t)) + N_{0s}$$

where

$N_t$  = NO<sub>3</sub>-N plus NH<sub>4</sub>-N concentration at time  $t$  (mg N kg<sup>-1</sup> dry soil);

$N_0$  = Potential inorganic N forming substrate in soil (mg N kg<sup>-1</sup> dry soil);

$N_{0s}$  = Initial inorganic N concentration in soil at  $t = 0$  (mg N kg<sup>-1</sup> dry soil);

$k$  = Inorganic N accumulation rate constant (week<sup>-1</sup>); and

$t$  = Time (weeks).

The model was used to estimate the parameters  $N_0$ ,  $N_{0s}$ , and  $k$ . Pairwise t tests of the weekly means for each depth were used to test for significance between treatments.

## RESULTS AND DISCUSSION

### Soil Nitrogen Mineralized

Due to the low crop response to N additions in 1999, a soil incubation study was attempted to determine potential plant-available N (PAN) released in 2000 due to mineralization of organic N (Fig. 5.1 and 5.2). All soil samples came from Section 1, except for the nearby pine forest soil. The pine forest soil was used as the control

because it had similar soil properties to the research plots and had not been fertilized. However, in the upper 0.15 m of soil, the pine forest released as much N ( $39 \text{ mg kg}^{-1}$ ) as did any soils from the fertilized plots (Fig. 5.1). Therefore, the pine forest soil was not the appropriate control for the mineralization study. The removal of undecomposed material (plant roots and leaf litter) from the soil may have allowed mineralization to occur without the released N being immobilized through microbial decomposition.

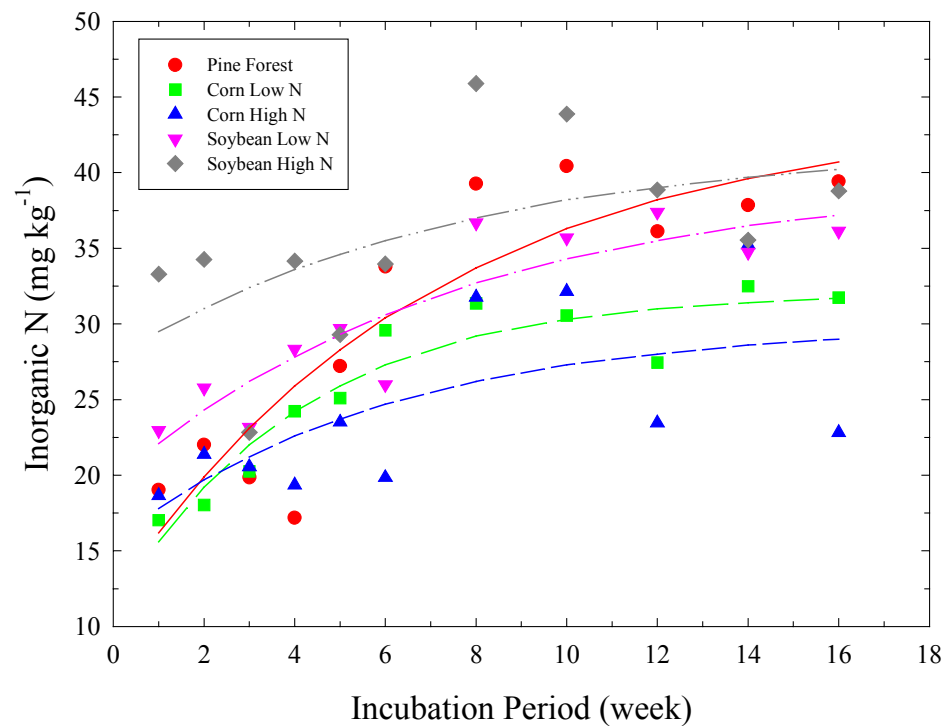


Fig. 5.1. Cumulative N mineralized in the upper 0.15 m of soil from the research plots and a nearby pine forest.

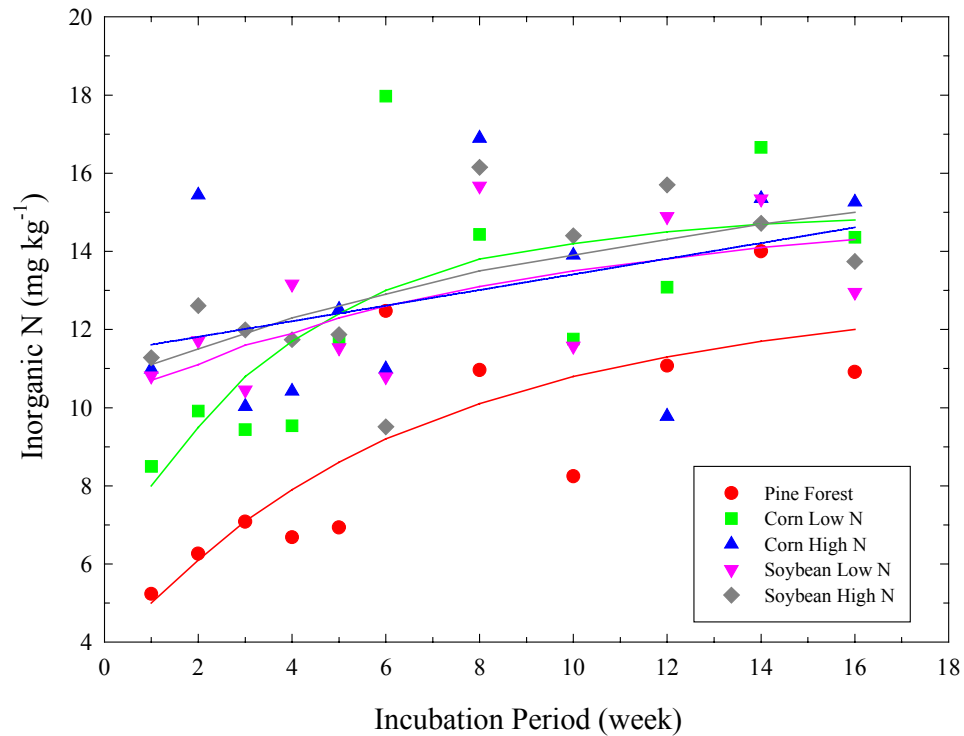


Fig. 5.2. Cumulative N mineralized from soil in the research plots and a nearby pine forest at the 0.15 to 0.30 m depth.

A first-order accumulation model (Chescheir et al., 1986) described the rate of inorganic N being released over time with the exception of high N corn at the 0.15 to 0.3 m depth. However, the model (Table 5.1) did not significantly ( $p < 0.05$ ) describe the N released for corn and soybean at high-applied N (0 – 0.15 m depth) and soybean at both high and low applied N rates (0.15 – 0.3 m depth). The model fit is affected by what appears to be experimental error occurring during sampling of weeks 8 and 10 (Fig. 5.1). The experimental error is believed to have been caused by contaminated KCl extraction solution.

Table 5.1. First-order model estimates for mineralized N accumulation from four field soils with a history of SLL applications and a nearby unfertilized pine forest in 2000<sup>†</sup>.

| Treatment              | Depth      | Applied N <sup>‡</sup><br>kg ha <sup>-1</sup> | Mean N <sup>§</sup><br>16 weeks | N <sub>0s</sub> |                     | N <sub>0</sub> |     | k         |                    | MODEL   |                |
|------------------------|------------|---|---------------------------------|-----------------|---------------------|----------------|-----|-----------|--------------------|---------|----------------|
|                        |            |   |                                 | Parameter       | SE <sup>¶</sup>     | Parameter      | SE  | Parameter | SE                 | Pr > F  | R <sup>2</sup> |
|                        | m          |   |                                 |                 | mg kg <sup>-1</sup> |                |     |           | week <sup>-1</sup> |         |                |
| Pine Forest            | 0 – 0.15   | 0   | 39                              | 12              | 5.8                 | 32             | 6.3 | 0.14      | 0.098              | 0.0015  | 0.80           |
| Corn Low               |            | 0 – 45  | 32                              | 11              | 3.2                 | 21             | 2.8 | 0.25      | 0.078              | <0.0001 | 0.90           |
| Corn High              |            | 119 – 190                                     | 23                              | 16              | 6.6                 | 14             | 6.1 | 0.16      | 0.240              | 0.1126  | 0.42           |
| Soybean Low            |            | 0 – 78  | 36                              | 20              | 3.4                 | 20             | 4.1 | 0.13      | 0.093              | 0.0011  | 0.82           |
| Soybean High           |            | 157 – 268                                     | 39                              | 28              | 7.3                 | 14             | 9.1 | 0.13      | 0.283              | 0.2125  | 0.32           |
| Pine Forest            | 0.15 – 0.3 | 0   | 11                              | 4               | 2.5                 | 9              | 2.4 | 0.15      | 0.145              | 0.0137  | 0.66           |
| Corn Low               |            | 0 – 45  | 14                              | 6               | 3.9                 | 9              | 3.4 | 0.26      | 0.224              | 0.0458  | 0.54           |
| Corn High <sup>#</sup> |            | 119 – 190                                     | 15                              | -               | -                   | -              | -   | -         | -                  | -       | -              |
| Soybean Low            |            | 0 – 78  | 13                              | 10              | 1.9                 | 5              | 3.7 | 0.11      | 0.228              | 0.1226  | 0.41           |
| Soybean High           |            | 157 – 268                                     | 14                              | 11              | 1.9                 | 6              | 9.2 | 0.07      | 0.216              | 0.1166  | 0.42           |

<sup>†</sup>Model equation  $N_t = N_0 * (1 - \exp(-k * t)) + N_{0s}$ .

<sup>‡</sup>Calculated applied N from SLL in 1999.

<sup>§</sup>Inorganic N consisted of NO<sub>3</sub>-N and NH<sub>4</sub>-N.

<sup>¶</sup>Asymptotic standard error. Standard error is an estimate since model is not a linear function.

<sup>#</sup>Data did not fit first-order model. Data was modeled using the best fit linear equation ( $Y = 11.4 + 0.20x$ ).



Based on the relatively high asymptotically standard errors for parameter estimates (Table 5.1), neither applied N nor crop had a significant influence on soil N mineralization. The standard errors were approximations since the model used did not follow a linear relationship throughout the incubation period. Excluding corn high N rate, no significant difference in treatments was observed in cumulative N released at the 0 to 0.15 m depth by week 16. At the 0.15 to 0.3 m depth, cumulative N released by week 16 was not significantly different between crop treatments. With the exception of soybean low-applied N treatment, N mineralization in the pine forest soil was significantly lower than any of the crop treatments by week 16. The k values listed in Table 5.1 for the crops are lower than the k values of 0.28 to 0.44 per week reported by Chescheir et al. (1986) for a Norfolk sand amended with 310 kg N ha<sup>-1</sup> of swine waste. In the same study, the Norfolk sand had a k value of 0.14 per week when no manure was added.

From the pairwise t tests of accumulated weekly inorganic N means within the 0 to 0.15 m soil depth (Table 5.2), no significant N application effect on mineralization was noticed. More N was mineralized in the upper 0.15 m of soil obtained from soybean than corn by week 12 at both N rates. The increase in N mineralized could have been influenced by the extra application of SLL to soybean in 1999. The additional SLL application allowed for a higher N rate at both Soybean Low and Soybean High than the corn treatments (see applied N in Table 5.1). Initially (1 week), significantly higher inorganic N amounts were measured for the Soybean High treatment at the 0 to 0.15 m soil depth (Table 5.2) than the other treatments. The higher inorganic N amounts do not appear to be an N rate effect since by the end of the study

no significant difference is noticed between N rates for soybean. For the 0.15 to 0.3 m soil depth (Table 5.3), inorganic N amounts obtained from either crop at any N application rate by the end of the study were not significantly different. However, any concrete conclusions from this mineralization study are hard to determine because of possible experimental error discussed earlier with the first-order accumulation model. Also, heavy rainfall in September 1999 from several hurricanes (Fig. 3.1) and SLL applications to the field in years prior to the research potentially impacted the mineralization study.

Using the mean N mineralization amount occurring from the Soybean High treatment for the 0 to 0.15 m soil depth by week 16 (Table 5.2), an estimated 86 kg N ha<sup>-1</sup> was released in 2000. This amount closely corresponds to the average grain N recovered from the corn control plot (73 kg N ha<sup>-1</sup>) but is higher than the grain N recovered from the nonnodulating soybean control plot (56 kg N ha<sup>-1</sup>). Since the control for the nonnodulating soybean received no extra water through irrigation, this may have limited N uptake. The corn control plot received additional water through irrigation.

In a corn fertility study of three North Carolina Coastal Plain soils, Kamprath (1986) reported a range of 25 to 90 kg N ha<sup>-1</sup> being released from the soil. In another study looking at the N nutrition of soybean grown in the North Carolina Coastal Plain, Israel and Burton (1997) found a range of 80 to 115 kg N ha<sup>-1</sup> coming from residual soil N. Both studies were conducted on fields where N fertilization had been used for crop production. Therefore, inorganic N amounts obtained from the mineralization experiment were similar to previous research.

Table 5.2. Summary of weekly inorganic N accumulation means from the four field soils and a nearby forest soil from the 0 to 0.15 m depth in 2000. Values within a week not sharing the same letter are significantly different at  $p < 0.05$ .

| Treatment    | Incubation Period (week)         |     |     |      |     |      |     |     |     |     |      |
|--------------|----------------------------------|-----|-----|------|-----|------|-----|-----|-----|-----|------|
|              | 1                                | 2   | 3   | 4    | 5   | 6    | 8   | 10  | 12  | 14  | 16   |
|              | -----mg N kg <sup>-1</sup> ----- |     |     |      |     |      |     |     |     |     |      |
| Pine Forest  | 19a                              | 22a | 20a | 17a  | 27a | 34a  | 39a | 40a | 36a | 38a | 39a  |
| Corn Low     | 17b                              | 18b | 20a | 24bc | 25a | 30ab | 31b | 30b | 27b | 32a | 32ab |
| Corn High    | 19a                              | 21a | 20a | 19ab | 24a | 20c  | 32b | 32b | 23b | 35a | 23b  |
| Soybean Low  | 23d                              | 26c | 23a | 28cd | 30a | 26b  | 37c | 36c | 37a | 35a | 36a  |
| Soybean High | 33d                              | 34d | 23a | 34d  | 29a | 34a  | 46d | 44d | 39a | 36a | 39a  |

Table 5.3. Summary of weekly inorganic N accumulation means from the four field soils and a nearby forest soil from the 0.15 to 0.3 m depth in 2000. Values within a week not sharing the same letter are significantly different at  $p < 0.05$ .

| Treatment    | Incubation Period (week)         |      |      |      |     |     |      |     |      |      |      |
|--------------|----------------------------------|------|------|------|-----|-----|------|-----|------|------|------|
|              | 1                                | 2    | 3    | 4    | 5   | 6   | 8    | 10  | 12   | 14   | 16   |
|              | -----mg N kg <sup>-1</sup> ----- |      |      |      |     |     |      |     |      |      |      |
| Pine Forest  | 5a                               | 6a   | 7a   | 7a   | 7a  | 12a | 11a  | 8a  | 11a  | 14a  | 11a  |
| Corn Low     | 8b                               | 10b  | 9b   | 10b  | 12b | 18b | 14b  | 12b | 13b  | 17b  | 14b  |
| Corn High    | 11c                              | 15c  | 10b  | 10bc | 12b | 11a | 17c  | 14c | 10a  | 15ab | 15b  |
| Soybean Low  | 11c                              | 12b  | 10bc | 13d  | 12b | 11a | 16d  | 12b | 15bc | 15ab | 13ab |
| Soybean High | 11c                              | 13bc | 12c  | 12cd | 12b | 10a | 16cd | 14c | 16c  | 15ab | 14b  |

### **Soil Inorganic Nitrogen Concentrations**

Overall, very little change in inorganic N present in the soil from the beginning to the end of the growing season was measured. Generally, soil inorganic N amounts did not significantly increase by the end of the growing season as SLL application rate increased (Fig. 5.3 and 5.4). Applied N from the fertilizer treatments significantly ( $p < 0.05$ ) increased soil inorganic N concentrations for corn at all depths in 1999 and at the 0.3 to 0.6 m depth in 2000 (Fig. 5.5 and Table 5.4). For soybean, increased residual soil N from the fertilizer treatment was significant only in 1999 at the 0.3 to 0.6 m and 0.6 to 0.9 m depths (Fig. 5.5 and Table 5.4). Applications of SLL significantly impacted soil inorganic N amounts only in 2000 (Fig. 5.4 and Table 5.4). Soil inorganic N amounts increased with increasing SLL applications to corn in Section 2 at the 0.6 to 0.9 m soil depth. For soybean in Section 2, inorganic soil N decreased with increasing SLL applications at the 0.3 to 0.6 m soil depth.

The higher inorganic soil N concentrations for 1999 corn in Section 2 at all depths was probably due to mineralization of soil organic N along with additions of SLL (Fig. 5.4). Higher soil N concentrations for 1999 were also noticed for the  $\text{NH}_4\text{NO}_3$  applications to corn (Fig. 5.5). Mineralization of soil N is suspected because of the grain N removed by the corn control in 1999 ( $101 \text{ kg N ha}^{-1}$ ), the relatively low soil inorganic N concentrations at the beginning of the year (see Appendix), and the history of SLL irrigated onto this field for many years.

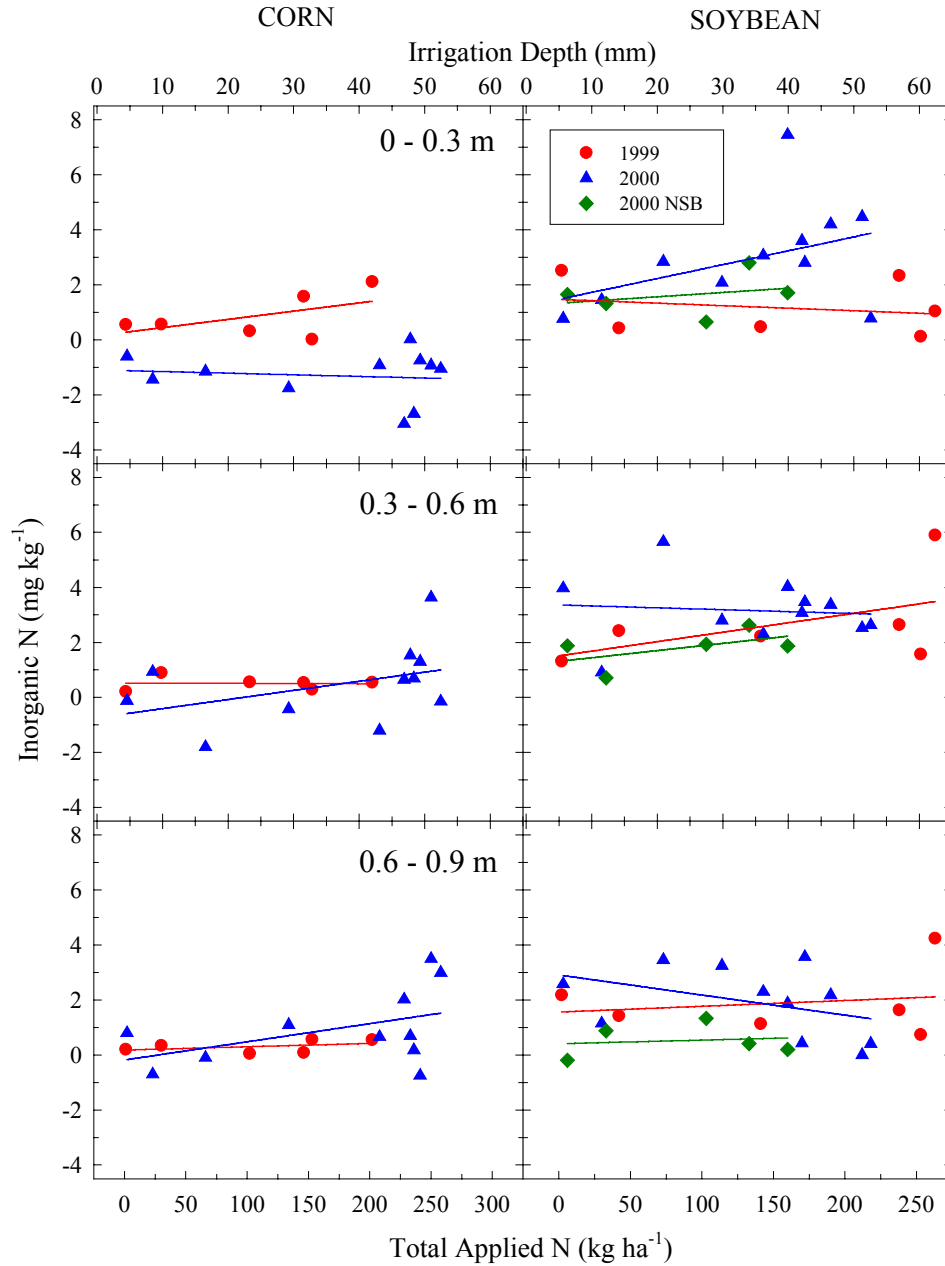


Fig. 5.3. Net change in soil inorganic N by depth within the growing season in Section 1 for corn, soybean, and nonnodulating soybean (NSB) receiving SLL. The change is estimated by the difference in soil inorganic N concentrations from preplant and post harvest soil samples.

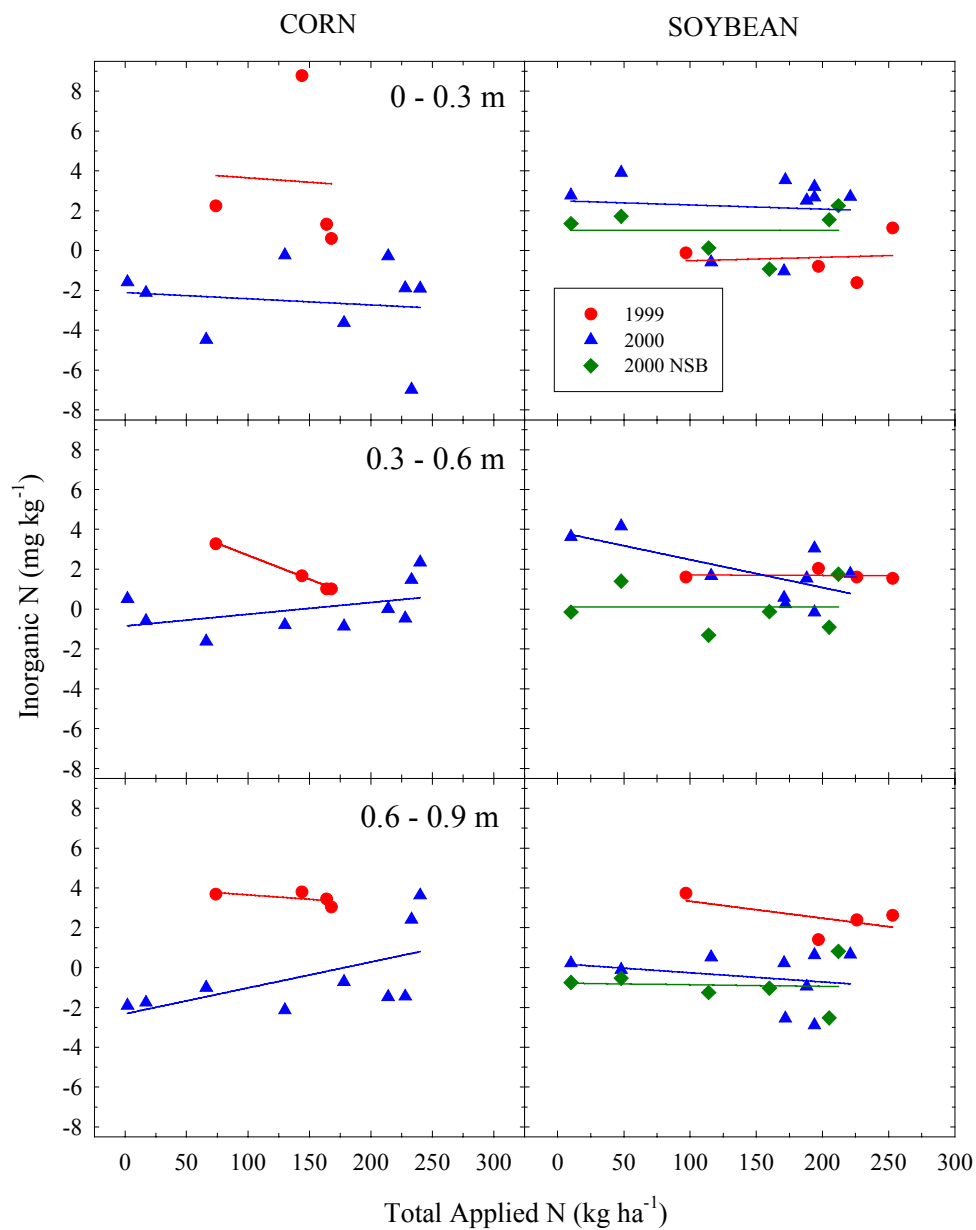


Fig. 5.4. Net change in soil inorganic N by depth within the growing season in Section 2 for corn, soybean, and nonnodulating soybean (NSB) receiving SLL and water. The change is estimated by the difference in soil inorganic N concentrations from preplant and post harvest soil samples.

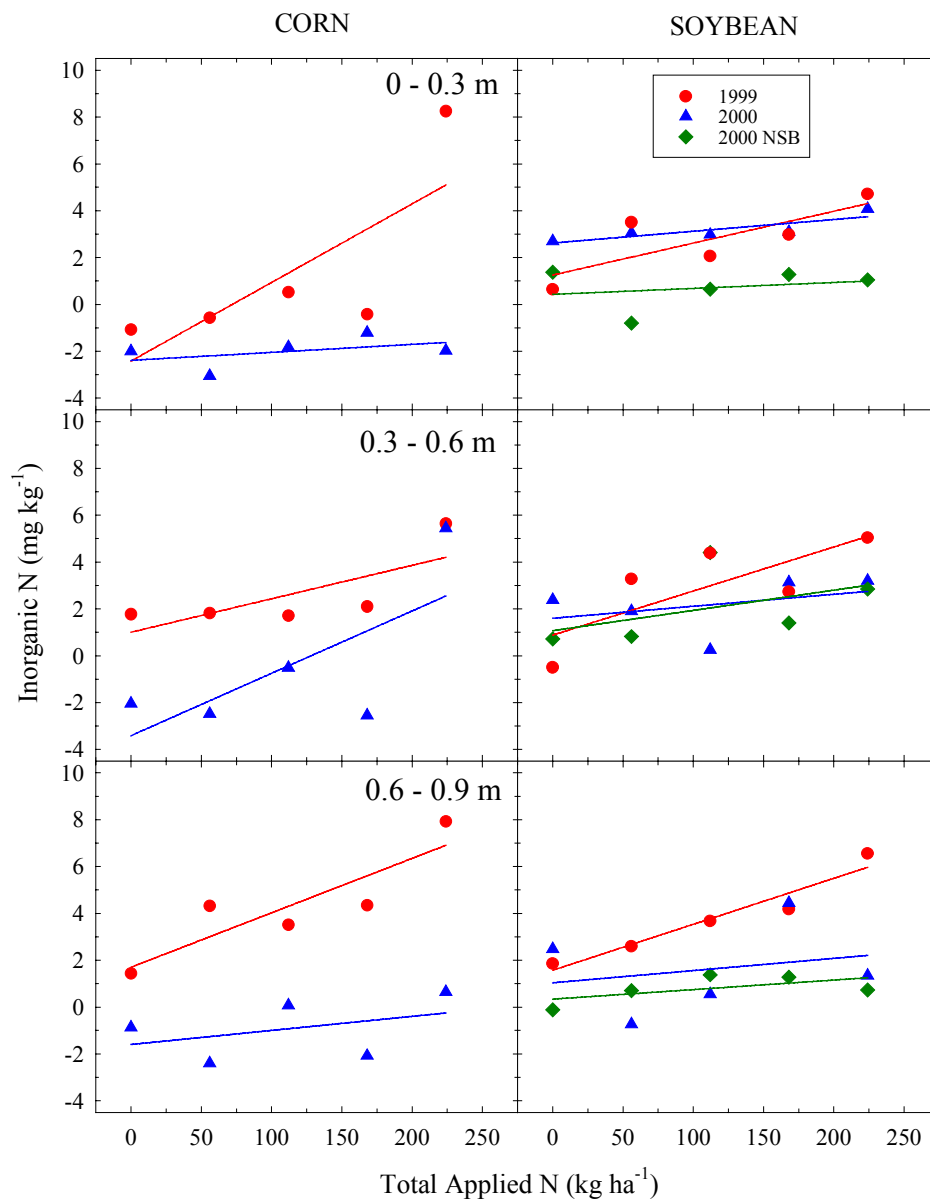


Fig. 5.5. Net change in soil inorganic N by depth within the growing season in Section 3 for corn, soybean, and nonnodulating soybean (NSB) receiving  $\text{NH}_4\text{NO}_3$  and variable water amounts. The change is estimated by the difference in soil inorganic N concentrations from preplant and post harvest soil samples.

Table 5.4. Trends found for the change in soil inorganic N within the growing season<sup>†</sup>.

| Crop <sup>‡</sup> | Section <sup>§</sup> | Depth       | 1999               |                     | 2000                |        |
|-------------------|----------------------|-------------|--------------------|---------------------|---------------------|--------|
|                   |                      |             | Equation           | Signf. <sup>¶</sup> | Equation            | Signf. |
| Corn              | 1                    | 0.0 - 0.3 m | = 0.0056x + 0.27   |                     | = -0.0011x - 1.12   |        |
| Corn              | 1                    | 0.3 - 0.6 m | = -0.00012x + 0.52 |                     | = 0.0062x + 0.60    |        |
| Corn              | 1                    | 0.6 - 0.9 m | = 0.0011x + 0.18   |                     | = 0.0066x - 0.18    |        |
| NSB               | 1                    | 0.0 - 0.3 m | -                  |                     | = 0.0034x + 1.33    |        |
| NSB               | 1                    | 0.3 - 0.6 m | -                  |                     | = 0.0057x + 1.31    |        |
| NSB               | 1                    | 0.6 - 0.9 m | -                  |                     | = 0.0013x + 0.41    |        |
| Soybean           | 1                    | 0.0 - 0.3 m | = -0.0020x + 1.47  |                     | = 0.011x + 1.47     |        |
| Soybean           | 1                    | 0.3 - 0.6 m | = 0.0075x + 1.51   |                     | = -0.0015x + 3.36   |        |
| Soybean           | 1                    | 0.6 - 0.9 m | = 0.0021x + 1.56   |                     | = -0.0073x + 2.91   |        |
|                   |                      |             |                    |                     |                     |        |
| Corn              | 2                    | 0.0 - 0.3 m | = -0.0057x + 4.01  |                     | = -0.0031x - 2.11   |        |
| Corn              | 2                    | 0.3 - 0.6 m | = -0.024x + 5.10   |                     | = 0.0059x - 0.85    |        |
| Corn              | 2                    | 0.6 - 0.9 m | = -0.0044x + 4.09  |                     | = 0.013x - 2.32     | *      |
| NSB               | 2                    | 0.0 - 0.3 m | -                  |                     | = -0.000026x + 1.02 |        |
| NSB               | 2                    | 0.3 - 0.6 m | -                  |                     | = -0.000033x + 0.11 |        |
| NSB               | 2                    | 0.6 - 0.9 m | -                  |                     | = -0.00081x - 0.78  |        |
| Soybean           | 2                    | 0.0 - 0.3 m | = 0.0017x - 0.68   |                     | = -0.0021x + 2.50   |        |
| Soybean           | 2                    | 0.3 - 0.6 m | = -0.00021x + 1.73 |                     | = -0.014x + 3.88    | *      |
| Soybean           | 2                    | 0.6 - 0.9 m | = -0.0085x + 4.18  |                     | = -0.0046x + 0.20   |        |
|                   |                      |             |                    |                     |                     |        |
| Corn              | 3                    | 0.0 - 0.3 m | = 0.034x - 2.42    | *                   | = 0.0034x - 2.39    |        |
| Corn              | 3                    | 0.3 - 0.6 m | = 0.014x + 1.00    | *                   | = 0.027x - 3.41     | **     |
| Corn              | 3                    | 0.6 - 0.9 m | = 0.023x + 1.70    | ***                 | = 0.0060x - 1.60    |        |
| NSB               | 3                    | 0.0 - 0.3 m | -                  |                     | = 0.0025x + 0.43    |        |
| NSB               | 3                    | 0.3 - 0.6 m | -                  |                     | = 0.0086x + 1.07    |        |
| NSB               | 3                    | 0.6 - 0.9 m | -                  |                     | = 0.0041x + 0.34    |        |
| Soybean           | 3                    | 0.0 - 0.3 m | = 0.014x + 1.25    |                     | = 0.0050x + 2.62    |        |
| Soybean           | 3                    | 0.3 - 0.6 m | = 0.019x + 0.88    | **                  | = 0.0051x + 1.60    |        |
| Soybean           | 3                    | 0.6 - 0.9 m | = 0.020x + 1.57    | **                  | = 0.0052x + 1.04    |        |

<sup>†</sup>Equations used in Figures 5.11, 5.12, and 5.13.

<sup>‡</sup>NSB represents nonnodulating soybean.

<sup>§</sup>Section 1 received only SLL applications. Section 2 received both SLL and water applications. Section 3 received NH<sub>4</sub>NO<sub>3</sub> applications and variable water amounts.

<sup>¶</sup>Slopes significant at the 0.05 (\*), 0.01 (\*\*), and 0.001 (\*\*\*) probability levels.



A further complicating factor occurred in 1999 when a portion of the field was flooded in September because of the heavy rainfall from several hurricanes (Fig. 3.1). The soil samples from the plots were not taken until November after the soybeans were harvested. While inorganic N concentrations were higher at all soil depths in Section 2 for 1999 than 2000 (Fig. 5.4) except for soybean at the 0 to 0.3 m depth, the actual amount of N leached is not known. Since inorganic N concentrations increased below the 0 to 0.3 m depth within the growing season, some of the  $\text{NO}_3^-$  was likely leached during these storm events. Also, the  $\text{NO}_3\text{-N}$  present below the 0.3 m depth at harvest will likely be unavailable for next year's crop due to leaching occurring during the winter months.

### **Nitrogen Budget**

Based on trends established earlier from crop and soil data, N budgets for 1999 and 2000 (Tables 5.5 and 5.6) were generated to compare SLL and  $\text{NH}_4\text{NO}_3$  for crop production. Since SLL was applied as a continuous variable and  $\text{NH}_4\text{NO}_3$  was applied in discrete amounts, SLL comparisons were made from the regression curves to match the actual  $\text{NH}_4\text{NO}_3$  application rates. The SLL N application rates shown in Tables 5.5 and 5.6 still reflect the content of N measured in the catch cups. Since the irrigation effect was minimized in Section 2, numbers for SLL were obtained from Section 2 trends. The numbers generated for the  $\text{NH}_4\text{NO}_3$  treatments are from trends considering all irrigation levels. Irrigation depths did not significant influence grain N removal from  $\text{NH}_4\text{NO}_3$  applications to corn and soybean in 1999 or 2000 (see Chapter 3). The nonnodulating soybean received no irrigation within the fertilizer treatments.

Table 5.5. Partial N budget for SLL applied by irrigation in Section 2 compared to fertilizer N treatments in 1999.

| Crop                              | N Source                        | Input                  |                                   |                   |       | Output        | N Remaining | Change in Soil N <sup>¶</sup> |
|-----------------------------------|---------------------------------|------------------------|-----------------------------------|-------------------|-------|---------------|-------------|-------------------------------|
|                                   |                                 | Applied N <sup>†</sup> | N <sub>2</sub> Fixed <sup>‡</sup> | Soil <sup>§</sup> | Total | Grain Removal |             |                               |
| ----- kg N ha <sup>-1</sup> ----- |                                 |                        |                                   |                   |       |               |             |                               |
| Corn                              | SLL                             | 56                     | -                                 | 116               | 172   | 118           | 54          | 51                            |
|                                   |                                 | 112                    | -                                 | 116               | 228   | 119           | 109         | 42                            |
|                                   |                                 | 168                    | -                                 | 116               | 284   | 121           | 163         | 33                            |
|                                   |                                 | 224                    | -                                 | 116               | 340   | 122           | 218         | -                             |
| Soybean                           |                                 | 56                     | 15                                | 116               | 187   | 137           | 50          | 22                            |
|                                   |                                 | 112                    | 11                                | 116               | 239   | 138           | 101         | 20                            |
|                                   |                                 | 168                    | 7                                 | 116               | 291   | 140           | 151         | 18                            |
|                                   |                                 | 224                    | 2                                 | 116               | 342   | 142           | 200         | 16                            |
| Corn                              | NH <sub>4</sub> NO <sub>3</sub> | 56                     | -                                 | 101               | 157   | 101           | 56          | 19                            |
|                                   |                                 | 112                    | -                                 | 101               | 213   | 101           | 112         | 37                            |
|                                   |                                 | 168                    | -                                 | 101               | 269   | 101           | 168         | 55                            |
|                                   |                                 | 224                    | -                                 | 101               | 325   | 102           | 223         | 73                            |
| Soybean                           |                                 | 56                     | 10                                | 101               | 167   | 116           | 51          | 30                            |
|                                   |                                 | 112                    | 5                                 | 101               | 218   | 113           | 105         | 43                            |
|                                   |                                 | 168                    | 2                                 | 101               | 271   | 109           | 162         | 56                            |
|                                   |                                 | 224                    | 0                                 | 101               | 325   | 105           | 220         | 70                            |

<sup>†</sup>SLL applied N reflects the amount recovered in catch cans immediately after irrigation. The rates are estimated from reported regressions in order to match NH<sub>4</sub>NO<sub>3</sub> application rates.

<sup>‡</sup>The amount of symbiotic N<sub>2</sub> fixation estimated from the acetylene reduction activity of soybean nodules. N fixed calculated by  $N_f = (\text{total grain N} - \text{soil N}) * ((100 - \% \text{ reduction}) / 100)$ .

<sup>§</sup>Soil N is the grain N removed at 0 kg of applied N and determined to be the intercept from the N removed equations. The soil N factor for the corn was also used for soybean.

<sup>¶</sup>Measured soil inorganic N in the upper 0.9 m of the soil. Based on trends in Figures 5.4 and 5.5. Assumed  $4.48 \times 10^6$  kg soil ha<sup>-1</sup> for a depth of 0.3 m.

Table 5.6. Partial N budget for SLL applied by irrigation in Section 2 compared to fertilizer N treatments in 2000.

| Crop                  | N Source                        | Input                  |                                   |                   |       | Output        | N Remaining | Change in Soil N <sup>¶</sup> |
|-----------------------|---------------------------------|------------------------|-----------------------------------|-------------------|-------|---------------|-------------|-------------------------------|
|                       |                                 | Applied N <sup>†</sup> | N <sub>2</sub> Fixed <sup>‡</sup> | Soil <sup>§</sup> | Total | Grain Removal |             |                               |
| kg N ha <sup>-1</sup> |                                 |                        |                                   |                   |       |               |             |                               |
| Corn                  | SLL                             | 56                     | -                                 | 81                | 137   | 97            | 40          | (-20)                         |
|                       |                                 | 112                    | -                                 | 81                | 193   | 112           | 81          | (-16)                         |
|                       |                                 | 168                    | -                                 | 81                | 249   | 128           | 121         | (-12)                         |
|                       |                                 | 224                    | -                                 | 81                | 305   | 144           | 161         | (-8)                          |
| NSB                   |                                 | 56                     | -                                 | 62                | 118   | 76            | 42          | 1                             |
|                       |                                 | 112                    | -                                 | 62                | 174   | 90            | 84          | 1                             |
|                       |                                 | 168                    | -                                 | 62                | 230   | 104           | 126         | 1                             |
|                       |                                 | 224                    | -                                 | 62                | 286   | 118           | 168         | 1                             |
| Soybean               |                                 | 56                     | 77                                | 62                | 195   | 167           | 28          | 24                            |
|                       |                                 | 112                    | 55                                | 62                | 229   | 164           | 65          | 19                            |
|                       |                                 | 168                    | 35                                | 62                | 265   | 162           | 103         | 14                            |
|                       |                                 | 224                    | 15                                | 62                | 301   | 160           | 141         | 9                             |
| Corn                  | NH <sub>4</sub> NO <sub>3</sub> | 56                     | -                                 | 73                | 129   | 106           | 23          | (-24)                         |
|                       |                                 | 112                    | -                                 | 73                | 185   | 131           | 54          | (-15)                         |
|                       |                                 | 168                    | -                                 | 73                | 241   | 148           | 93          | (-6)                          |
|                       |                                 | 224                    | -                                 | 73                | 297   | 158           | 139         | 3                             |
| NSB                   |                                 | 56                     | -                                 | 56                | 112   | 73            | 39          | 12                            |
|                       |                                 | 112                    | -                                 | 56                | 168   | 91            | 77          | 16                            |
|                       |                                 | 168                    | -                                 | 56                | 224   | 108           | 116         | 20                            |
|                       |                                 | 224                    | -                                 | 56                | 280   | 125           | 155         | 23                            |
| Soybean               |                                 | 56                     | 99                                | 56                | 211   | 201           | 10          | 27                            |
|                       |                                 | 112                    | 85                                | 56                | 253   | 210           | 43          | 31                            |
|                       |                                 | 168                    | 69                                | 56                | 293   | 219           | 74          | 35                            |
|                       |                                 | 224                    | 51                                | 56                | 331   | 228           | 103         | 39                            |

<sup>†</sup>SLL applied N reflects the amount recovered in catch cans immediately after irrigation. The rates are estimated from reported regressions in order to match NH<sub>4</sub>NO<sub>3</sub> application rates.

<sup>‡</sup>The amount of symbiotic N<sub>2</sub> fixation estimated from the acetylene reduction activity of soybean nodules. N fixed calculated by  $N_f = (\text{total grain N} - \text{soil N}) * ((100 - \% \text{ reduction}) / 100)$ .

<sup>§</sup>Soil N is the grain N removed at 0 kg of applied N and determined to be the intercept from the N removed equations. The soil N factor for the nonnodulating soybean (NSB) was also used for soybean.

<sup>¶</sup>Measured soil inorganic N in the upper 0.9 m of the soil. Based on trends in Figures 5.4 and 5.5. Assumed  $4.48 \times 10^6$  kg soil ha<sup>-1</sup> for a depth of 0.3 m.

Less of the applied N was accounted for in 1999 (Table 5.5) than in 2000 (Table 5.6) for both SLL and  $\text{NH}_4\text{NO}_3$ . In 1999, N remaining after grain removal from corn and soybean was not different whether the applied N came from SLL or  $\text{NH}_4\text{NO}_3$ . The calculation for the  $224 \text{ kg N ha}^{-1}$  SLL rate for corn in 1999 was omitted because the maximum applied N rate was only  $215 \text{ kg N ha}^{-1}$ . The similar N balances between corn and soybean in 1999 was probably due to the amount of N released from the soil and the reduced  $\text{N}_2$  fixation by the soybean. Some of the N not removed by the grain appeared as increases in calculated soil inorganic N concentrations (upper 0.9 m). The concentrations of inorganic N in the soil during spring 2000 were similar to 1999 spring soil inorganic N concentrations suggesting very little winter carryover of inorganic N. With very little carryover of inorganic soil N, the majority of the soil inorganic N listed in Table 5.5 was probably lost from the root zone by leaching or denitrification.

More of the applied N was accounted for in grain removal in 2000 (Table 5.6) for all crops. The crops consistently removed more of the applied N from  $\text{NH}_4\text{NO}_3$  than from SLL. Estimated plant-available N mineralized from the soil decreased by >28%, however the amount of  $\text{N}_2$  fixation in soybean increased by >80%. Corn lowered the concentration of soil inorganic N for all applied N rates except for the  $224 \text{ kg N ha}^{-1}$  of  $\text{NH}_4\text{NO}_3$ . The nodulating soybean increased soil inorganic N amounts for both N sources. Since the corn was harvested by early September, any remaining inorganic N in the soil could have been immobilized during microbial decomposition of plant residues. Also, there was some indication of leaching occurring in the corn treatments with soil inorganic N concentrations increasing with depth when N application rates exceeded  $200 \text{ kg N ha}^{-1}$  (Fig. 5.3, 5.4, and 5.5).

Based on grain N removed and a lower N balance in 2000 for both N sources (Table 5.6), the nodulating soybean appears to be a better receiver crop of SLL than nonnodulating soybean or corn. However, if the amount of N<sub>2</sub> fixed is underestimated, then there would be less of a difference between the nodulating soybean versus corn or nonnodulating soybean. The actual amount of symbiotic N<sub>2</sub> fixation by the nodulating soybean is not known, but is estimated based on one measurement of acetylene reduction activity of soybean nodules (see Chapter 4).

A remaining question with soybeans is how much N they return to the soil for next year's crop. Typically, a credit of 15 to 35 kg N ha<sup>-1</sup> is given to the next crop when soybean was the previous crop (Israel and Burton, 1997; Zublena et al., 1990). However, Israel and Burton (1997) suggested that the soybean N credit could lead to under fertilization when following a high yielding nodulating soybean crop with a nonleguminous crop. Typically, they found that residual soil N tends to increase when the amount of symbiotic N<sub>2</sub> fixation is greater than the amount of N removed in the grain.

By comparing the estimated soil N released to corn and soybean in 1999 and 2000 (Tables 5.5 and 5.6), soil inorganic N amounts were lower for soybean than for corn in 2000. The lower inorganic amounts suggest that soybean removed more soil N in 1999 than did corn. However, little N<sub>2</sub> fixation occurred in 1999. With increased N<sub>2</sub> fixation measured in 2000, soil inorganic N amounts should not have decreased as much as from 1999 to 2000. Since no measurements were made in 2001, the continued impact of increased N<sub>2</sub> fixation on residual soil N was not measured.

## CONCLUSIONS

Overall, applied N was removed more efficiently by nodulating soybean than by corn. Also, corn and soybean were more efficient in utilizing  $\text{NH}_4\text{NO}_3$  than SLL applied by irrigation. Since the applied N from SLL was based on the N contents within the catch cups, the calculated applied N accounted only for volatilization losses during irrigation. However after irrigation, the calculated applied N was subject to further potential losses such as volatilization, denitrification, and leaching during the growing season. In conjuncture with this research project, Byers (1999) and Hernandez et al. (2000) attempted to measure volatilization and denitrification losses after the SLL had been applied. The estimated volatilization losses were in question because >100% of the applied N was removed by volatilization. Hernandez et al. (2000) estimated N losses through denitrification to range from 8 to 19% of the total applied N.

In 1999, the large amounts of N mineralized from the soil decreased crop uptake of applied N from both SLL and  $\text{NH}_4\text{NO}_3$ . More efficient crop N uptake from both N sources was noticed in 2000 for both corn and soybean. Based on N remaining after the growing season (total input – grain N removal), the potential for N losses to the environment was greater in 1999 than 2000 for all crops and N sources. However, not all of the unaccounted N would be lost, since some of the applied N is present in plant residues remaining in the field.

It has been proven that SLL can be used as a source of N for crop production to obtain similar yields as from inorganic N fertilizers. However, when applying organic wastes to land for crop production, obtaining a realistic yield is only one of the issues deserving consideration (Mikkelsen, 2000b). Also, the fertilizer N equivalency of SLL

applied by irrigation is very difficult to pinpoint due to occurring N transformations, the influence of climate and soil properties on N transformations, and the variations in N content of the SLL. Errors in predicting the fertilizer N equivalency of SLL can lead to under or over fertilization of the crop. As with inorganic N fertilizers, excessive N applications with respect to producing realistic crop yields potentially leads to negative environmental impacts.

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## **APPENDIX**

Table A.1. Data collected for the pattern determination of sprinkler 70CW-TNT shown in Fig. 2.3<sup>†</sup>.

| Distance From Sprinkler                                  | Transects <sup>‡</sup>          |    |    |    |    |   |    |   |
|--|---------------------------------|----|----|----|----|---|----|---|
|  | A                               | B  | C  | D  | E  | F | G  | H |
| m  | ----- mm hr <sup>-1</sup> ----- |    |    |    |    |   |    |   |
| (a) 580 kPa sprinkler pressure                           |                                 |    |    |    |    |   |    |   |
| 2.4  | 7                               | 7  | 6  | 6  | 6  | 6 | 8  | 8 |
| 4.9  | 5                               | 5  | 5  | 5  | 5  | 4 | 5  | 4 |
| 7.3  | 4                               | 5  | 6  | 6  | 6  | 5 | 5  | 4 |
| 9.7  | 6                               | 7  | 8  | 8  | 8  | 8 | 6  | 6 |
| 12.2   | 10                              | 10 | 10 | 10 | 10 | 9 | 9  | 8 |
| 14.6   | 12                              | 10 | 8  | 6  | 8  | 9 | 9  | 9 |
| 17.0   | 4                               | 2  | 1  | 1  | 1  | 1 | 4  | 5 |
| 19.5   | 0                               | 0  | 0  | 0  | 0  | 0 | 0  | 1 |
| 21.9   | 0                               | 0  | 0  | 0  | 0  | 0 | 0  | 0 |
| 24.3   | 0                               | 0  | 0  | 0  | 0  | 0 | 0  | 0 |
| (b) 440 kPa sprinkler pressure                           |                                 |    |    |    |    |   |    |   |
| 2.4  | 6                               | 6  | 5  | 5  | 6  | 5 | 5  | 7 |
| 4.9  | 4                               | 4  | 5  | 6  | 6  | 4 | 4  | 4 |
| 7.3  | 3                               | 5  | 6  | 6  | 6  | 4 | 4  | 3 |
| 9.7  | 5                               | 7  | 8  | 8  | 7  | 6 | 5  | 4 |
| 12.2   | 8                               | 9  | 9  | 9  | 9  | 8 | 7  | 6 |
| 14.6   | 10                              | 9  | 5  | 3  | 5  | 9 | 10 | 9 |
| 17.0   | 3                               | 0  | 0  | 0  | 0  | 0 | 4  | 5 |
| 19.5   | 0                               | 0  | 0  | 0  | 0  | 0 | 0  | 0 |
| 21.9   | 0                               | 0  | 0  | 0  | 0  | 0 | 0  | 0 |
| 24.3   | 0                               | 0  | 0  | 0  | 0  | 0 | 0  | 0 |
| (c) 470 kPa sprinkler pressure and no straightening vane |                                 |    |    |    |    |   |    |   |
| 2.4  | 8                               | 6  | 7  | 7  | 7  | 6 | 8  | 8 |
| 4.9  | 5                               | 5  | 6  | 6  | 6  | 5 | 6  | 5 |
| 7.3  | 5                               | 5  | 7  | 7  | 5  | 5 | 4  | 4 |
| 9.7  | 6                               | 7  | 8  | 8  | 7  | 6 | 5  | 5 |
| 12.2   | 7                               | 8  | 8  | 8  | 7  | 6 | 6  | 6 |
| 14.6   | 7                               | 6  | 6  | 6  | 6  | 6 | 7  | 6 |
| 17.0   | 6                               | 5  | 4  | 3  | 5  | 6 | 5  | 6 |
| 19.5   | 4                               | 2  | 1  | 1  | 1  | 5 | 5  | 4 |
| 21.9   | 0                               | 0  | 0  | 0  | 0  | 0 | 1  | 1 |
| 24.3   | 0                               | 0  | 0  | 0  | 0  | 0 | 0  | 0 |

<sup>†</sup> Sprinkler tests performed during the evening with no measurable wind.

<sup>‡</sup> Transects placed 45° apart.

Table A.2. Data collected for the pattern determination of sprinkler 80E-TNT shown in Fig. 2.4<sup>†</sup>.

| Distance From Sprinkler                                | Transects <sup>‡</sup>         |    |    |    |    |    |    |    |
|--|--------------------------------|----|----|----|----|----|----|----|
|  | A                              | B  | C  | D  | E  | F  | G  | H  |
| m  | ----- mm h <sup>-1</sup> ----- |    |    |    |    |    |    |    |
| (a) 520 kPa sprinkler pressure with spreader nozzle    |                                |    |    |    |    |    |    |    |
| 2.4  | 13                             | 13 | 13 | 13 | 14 | 13 | 13 | 14 |
| 4.9  | 10                             | 11 | 11 | 11 | 11 | 10 | 10 | 11 |
| 7.3  | 8                              | 9  | 11 | 12 | 11 | 9  | 8  | 8  |
| 9.7  | 9                              | 11 | 12 | 14 | 12 | 10 | 10 | 9  |
| 12.2   | 9                              | 10 | 11 | 12 | 11 | 10 | 10 | 9  |
| 14.6   | 7                              | 8  | 10 | 9  | 9  | 8  | 8  | 7  |
| 17.0   | 6                              | 7  | 8  | 7  | 7  | 8  | 8  | 6  |
| 19.5   | 6                              | 7  | 6  | 4  | 5  | 6  | 7  | 6  |
| 21.9   | 6                              | 5  | 3  | 2  | 2  | 4  | 6  | 6  |
| 24.3   | 4                              | 2  | 1  | 1  | 0  | 1  | 4  | 4  |
| 26.8   | 1                              | 0  | 0  | 0  | 0  | 0  | 1  | 2  |
| 29.2   | 0                              | 0  | 0  | 0  | 0  | 0  | 0  | 0  |
| 31.6   | 0                              | 0  | 0  | 0  | 0  | 0  | 0  | 0  |
| (b) 520 kPa sprinkler pressure without spreader nozzle |                                |    |    |    |    |    |    |    |
| 2.4  | 11                             | 10 | 9  | 9  | 9  | 9  | 7  | 10 |
| 4.9  | 11                             | 8  | 7  | 5  | 7  | 9  | 8  | 10 |
| 7.3  | 10                             | 10 | 7  | 5  | 6  | 7  | 7  | 8  |
| 9.7  | 11                             | 10 | 7  | 5  | 7  | 7  | 4  | 9  |
| 12.2   | 11                             | 9  | 6  | 5  | 8  | 7  | 4  | 10 |
| 14.6   | 9                              | 6  | 5  | 5  | 8  | 9  | 5  | 11 |
| 17.0   | 5                              | 2  | 4  | 5  | 6  | 10 | 6  | 11 |
| 19.5   | 1                              | 0  | 2  | 5  | 3  | 9  | 7  | 8  |
| 21.9   | 0                              | 0  | 0  | 3  | 1  | 6  | 8  | 5  |
| 24.3   | 0                              | 0  | 0  | 1  | 0  | 3  | 7  | 1  |
| 26.8   | 0                              | 0  | 0  | 0  | 0  | 1  | 5  | 0  |
| 29.2   | 0                              | 0  | 0  | 0  | 0  | 0  | 1  | 0  |
| 31.6   | 0                              | 0  | 0  | 0  | 0  | 0  | 0  | 0  |

<sup>†</sup> Sprinkler tests performed during the evening with no measurable wind for test (a). For test (b), wind speed ranged from 0.9 to 2.7 m s<sup>-1</sup> in the direction of transect G away from sprinkler.

<sup>‡</sup> Transects placed 45° apart.

Table A.3. Data collected for the pattern determination of sprinkler 7525-1-1M at 621 kPa shown in Fig. 2.5<sup>†</sup>.

| Distance From Sprinkler | Transects <sup>‡</sup> |    |    |    |    |
|-------------------------|------------------------|----|----|----|----|
|                         | A                      | B  | C  | D  | E  |
| m                       | mm h <sup>-1</sup>     |    |    |    |    |
| 2.4                     | 16                     | 26 | 25 | 23 | 16 |
| 4.9                     | 13                     | 19 | 18 | 14 | 12 |
| 7.3                     | 10                     | 10 | 10 | 9  | 9  |
| 9.7                     | 9                      | 9  | 9  | 9  | 9  |
| 12.2                    | 10                     | 10 | 9  | 10 | 10 |
| 14.6                    | 11                     | 10 | 9  | 9  | 11 |
| 17.0                    | 11                     | 9  | 8  | 8  | 10 |
| 19.5                    | 8                      | 7  | 6  | 6  | 7  |
| 21.9                    | 3                      | 4  | 3  | 3  |    |
| 24.3                    |                        | 0  | 0  | 0  |    |

<sup>†</sup> Sprinkler tests performed during the evening with no measurable wind.

<sup>‡</sup> Transects placed 45° apart within a half circle.

Table A.4. Irrigation depths for June 7, 1999 for both SLL and water applications<sup>†</sup>.

| Distance <sup>‡</sup> | Transect Location <sup>§</sup> |    |    |    |    |    |    |    |    |    |    |    |
|-----------------------|--------------------------------|----|----|----|----|----|----|----|----|----|----|----|
|                       | 9                              | 13 | 16 | 36 | 39 | 43 | 63 | 66 | 70 | 83 | 86 | 90 |
| m                     | mm                             |    |    |    |    |    |    |    |    |    |    |    |
| 0.0                   | 0                              | 0  |    | 0  | 0  |    | 0  | 0  |    |    | 0  | 0  |
| 1.5                   |                                |    | 1  |    |    | 1  |    |    | 1  | 0  |    |    |
| 3.0                   | 0                              | 1  |    | 3  | 2  |    | 2  | 1  |    |    | 0  | 0  |
| 4.6                   |                                |    | 3  |    |    | 4  |    |    | 3  | 1  |    |    |
| 6.1                   | 3                              | 4  |    | 8  | 14 |    | 5  | 7  |    |    | 2  | 1  |
| 7.6                   |                                |    | 8  |    |    | 13 |    |    | 9  | 7  |    |    |
| 9.1                   | 6                              | 8  |    | 13 | 15 |    | 12 | 11 |    |    | 8  | 6  |
| 10.6                  |                                |    | 11 |    |    | 20 |    |    | 14 | 12 |    |    |
| 12.2                  | 9                              | 11 |    | 19 | 18 |    | 14 | 15 |    |    | 13 | 11 |
| 13.7                  |                                |    | 12 |    |    | 20 |    |    | 20 | 14 |    |    |
| 15.2                  | 11                             | 11 |    | 22 | 21 |    | 18 | 17 |    |    | 13 | 11 |
| 16.7                  |                                |    | 13 |    |    | 20 |    |    | 20 | 12 |    |    |
| 18.2                  | 12                             | 12 |    | 24 | 22 |    | 20 | 20 |    |    | 11 | 10 |
| 19.8                  |                                |    | 11 |    |    | 19 |    |    | 18 | 11 |    |    |
| 21.3                  | 12                             | 12 |    | 23 | 20 |    | 23 | 20 |    |    | 9  | 9  |
| 22.8                  |                                |    | 12 |    |    | 18 |    |    | 16 | 12 |    |    |
| 24.3                  | 13                             | 11 |    | 23 | 21 |    | 20 | 22 |    |    | 10 | 8  |
| 25.8                  |                                |    | 17 |    |    | 23 |    |    | 20 | 15 |    |    |
| 27.4                  | 12                             | 18 |    | 19 | 23 |    | 23 | 24 |    |    | 18 | 9  |
| 28.9                  |                                |    | 16 |    |    | 23 |    |    | 21 | 18 |    |    |
| 30.4                  | 13                             | 18 |    | 23 | 22 |    | 21 | 26 |    |    | 17 | 10 |
| 31.9                  |                                |    | 17 |    |    | 24 |    |    | 23 | 17 |    |    |
| 33.4                  | 12                             | 18 |    | 21 | 23 |    | 21 | 25 |    |    | 16 | 11 |
| 35.0                  |                                |    | 17 |    |    | 22 |    |    | 26 | 16 |    |    |
| 36.5                  | 16                             | 17 |    | 24 | 23 |    | 25 | 26 |    |    | 17 | 14 |
| 38.0                  |                                |    | 21 |    |    | 26 |    |    | 22 | 21 |    |    |
| 39.5                  | 20                             | 24 |    | 30 | 29 |    | 29 | 33 |    |    | 20 | 20 |
| 41.0                  |                                |    | 28 |    |    | 30 |    |    | 32 | 27 |    |    |
| 42.6                  | 25                             | 27 |    | 35 | 33 |    | 32 | 34 |    |    | 25 | 22 |
| 44.1                  |                                |    | 32 |    |    | 37 |    |    | 35 | 29 |    |    |
| 45.6                  | 22                             | 26 |    | 38 | 39 |    | 32 | 33 |    |    | 24 | 22 |
| 47.1                  |                                |    | 27 |    |    | 36 |    |    | 39 | 30 |    |    |
| 48.6                  | 18                             | 22 |    | 32 | 38 |    | 29 | 30 |    |    | 22 | 20 |
| 50.2                  |                                |    | 24 |    |    | 34 |    |    | 34 | 25 |    |    |
| 51.7                  | 15                             | 17 |    | 28 | 31 |    | 26 | 28 |    |    | 19 | 15 |
| 53.2                  |                                |    | 17 |    |    | 28 |    |    | 31 | 20 |    |    |
| 54.7                  | 21                             | 15 |    | 27 | 42 |    | 24 | 26 |    |    | 14 | 11 |
| 56.2                  |                                |    | 15 |    |    | 23 |    |    | 24 | 14 |    |    |
| 57.8                  | 19                             | 19 |    | 26 | 26 |    | 24 | 25 |    |    | 17 | 18 |
| 59.3                  |                                |    | 19 |    |    | 26 |    |    | 24 | 14 |    |    |
| 60.8                  | 17                             | 20 |    | 21 | 25 |    | 21 | 25 |    |    | 15 | 15 |
| 62.3                  |                                |    | 21 |    |    | 24 |    |    | 23 | 13 |    |    |
| 63.8                  | 19                             | 18 |    | 27 | 27 |    | 23 | 23 |    |    | 12 | 14 |
| 65.4                  |                                |    | 15 |    |    | 20 |    |    | 21 | 12 |    |    |
| 66.9                  | 17                             | 14 |    | 32 | 31 |    | 29 | 20 |    |    | 11 | 10 |
| 68.4                  |                                |    | 16 |    |    | 22 |    |    | 21 | 13 |    |    |
| 69.9                  | 13                             | 15 |    | 23 | 22 |    | 17 | 17 |    |    | 12 | 11 |
| 71.4                  |                                |    | 17 |    |    | 22 |    |    | 19 | 14 |    |    |
| 73.0                  | 14                             | 17 |    | 23 | 22 |    | 17 | 17 |    |    | 13 | 11 |
| 74.5                  |                                |    | 18 |    |    | 21 |    |    | 18 | 15 |    |    |
| 76.0                  | 15                             | 17 |    | 21 | 21 |    | 16 | 16 |    |    | 13 | 11 |
| 77.5                  |                                |    | 17 |    |    | 19 |    |    | 15 | 14 |    |    |
| 79.0                  | 11                             | 14 |    | 16 | 16 |    | 14 | 13 |    |    | 11 | 10 |
| 80.6                  |                                |    | 11 |    |    | 12 |    |    | 11 | 11 |    |    |
| 82.1                  | 5                              | 6  |    | 9  | 9  |    | 10 | 9  |    |    | 7  | 8  |
| 83.6                  |                                |    | 5  |    |    | 5  |    |    | 6  | 6  |    |    |
| 85.1                  | 1                              | 2  |    | 2  | 2  |    | 5  | 4  |    |    | 4  | 5  |
| 86.6                  |                                |    | 1  |    |    | 2  |    |    | 3  | 2  |    |    |
| 88.2                  | 0                              | 0  |    | 0  | 0  |    | 1  | 1  |    |    | 1  | 1  |
| 89.7                  |                                |    | 0  |    |    | 0  |    |    | 0  | 1  |    |    |
| 91.2                  | 0                              | 0  |    | 0  | 0  |    | 0  | 0  |    |    | 0  | 0  |

<sup>†</sup>Details about irrigation event listed in Table 2.2.

<sup>‡</sup>Swine lagoon liquid irrigation line at 30.4 m and the water line at 60.8 m.

<sup>§</sup>Transect location is in row numbers. Rows are 0.9 m apart.

Table A.5. Irrigation depths for June 23, 1999 for both SLL and water applications<sup>†</sup>.

| Distance <sup>‡</sup> | Transect Location <sup>§</sup> |    |    |    |    |    |    |    |    |    |    |    |
|-----------------------|--------------------------------|----|----|----|----|----|----|----|----|----|----|----|
|                       | 9                              | 13 | 16 | 36 | 39 | 43 | 63 | 66 | 70 | 83 | 86 | 90 |
| m                     | mm                             |    |    |    |    |    |    |    |    |    |    |    |
| 0.0                   | 0                              | 0  |    | 0  | 0  |    | 0  | 0  |    |    | 0  | 0  |
| 1.5                   |                                |    | 0  |    |    | 0  |    |    | 0  | 0  |    |    |
| 3.0                   | 0                              | 0  |    | 0  | 0  |    | 0  | 0  |    |    | 0  | 0  |
| 4.6                   |                                |    | 0  |    |    | 0  |    |    | 0  | 0  |    |    |
| 6.1                   | 0                              | 0  |    | 0  | 0  |    | 0  | 0  |    |    | 0  | 0  |
| 7.6                   |                                |    | 0  |    |    | 0  |    |    | 0  | 0  |    |    |
| 9.1                   | 0                              | 0  |    | 0  | 0  |    | 2  | 0  |    |    | 0  | 0  |
| 10.6                  |                                |    | 1  |    |    | 2  |    |    | 2  | 1  |    |    |
| 12.2                  | 1                              | 1  |    | 3  | 3  |    | 4  | 2  |    |    | 1  | 1  |
| 13.7                  |                                |    | 3  |    |    | 4  |    |    | 5  | 4  |    |    |
| 15.2                  | 2                              | 3  |    | 5  | 5  |    | 5  | 7  |    |    | 5  | 3  |
| 16.7                  |                                |    | 4  |    |    | 6  |    |    | 10 | 8  |    |    |
| 18.2                  | 3                              | 4  |    | 9  | 8  |    | 9  | 11 |    |    | 7  | 6  |
| 19.8                  |                                |    | 5  |    |    | 8  |    |    | 13 | 8  |    |    |
| 21.3                  | 3                              | 4  |    | 10 | 10 |    | 11 | 13 |    |    | 7  | 7  |
| 22.8                  |                                |    | 5  |    |    | 10 |    |    | 14 | 8  |    |    |
| 24.3                  | 3                              | 4  |    | 12 | 14 |    | 11 | 14 |    |    | 7  | 6  |
| 25.8                  |                                |    | 5  |    |    | 13 |    |    | 14 | 9  |    |    |
| 27.4                  | 3                              | 4  |    | 11 | 13 |    | 11 | 12 |    |    | 9  | 7  |
| 28.9                  |                                |    | 8  |    |    | 15 |    |    | 19 | 14 |    |    |
| 30.4                  | 3                              | 7  |    | 13 | 16 |    | 12 | 15 |    |    | 11 | 6  |
| 31.9                  |                                |    | 12 |    |    | 18 |    |    | 20 | 11 |    |    |
| 33.4                  | 4                              | 8  |    | 17 | 20 |    | 13 | 14 |    |    | 12 | 7  |
| 35.0                  |                                |    | 12 |    |    | 19 |    |    | 13 | 11 |    |    |
| 36.5                  | 4                              | 8  |    | 18 | 18 |    | 13 | 14 |    |    | 8  | 8  |
| 38.0                  |                                |    | 12 |    |    | 16 |    |    | 14 | 8  |    |    |
| 39.5                  | 5                              | 7  |    | 15 | 17 |    | 11 | 12 |    |    | 8  | 7  |
| 41.0                  |                                |    | 10 |    |    | 14 |    |    | 15 | 8  |    |    |
| 42.6                  | 6                              | 6  |    | 15 | 17 |    | 12 | 12 |    |    | 9  | 8  |
| 44.1                  |                                |    | 9  |    |    | 18 |    |    | 12 | 12 |    |    |
| 45.6                  | 7                              | 7  |    | 18 | 19 |    | 15 | 17 |    |    | 13 | 10 |
| 47.1                  |                                |    | 12 |    |    | 21 |    |    | 13 | 14 |    |    |
| 48.6                  | 10                             | 11 |    | 20 | 23 |    | 18 | 12 |    |    | 18 | 14 |
| 50.2                  |                                |    | 15 |    |    | 24 |    |    | 23 | 17 |    |    |
| 51.7                  | 13                             | 15 |    | 23 | 24 |    | 20 | 20 |    |    | 21 | 17 |
| 53.2                  |                                |    | 17 |    |    | 19 |    |    | 20 | 23 |    |    |
| 54.7                  | 12                             | 15 |    | 25 | 27 |    | 23 | 22 |    |    | 21 | 16 |
| 56.2                  |                                |    | 16 |    |    | 24 |    |    | 20 | 22 |    |    |
| 57.8                  | 13                             | 15 |    | 26 | 28 |    | 24 | 23 |    |    | 17 | 14 |
| 59.3                  |                                |    | 18 |    |    | 27 |    |    | 20 | 18 |    |    |
| 60.8                  | 15                             | 17 |    | 29 | 30 |    | 23 | 23 |    |    | 14 | 19 |
| 62.3                  |                                |    | 17 |    |    | 24 |    |    | 21 | 18 |    |    |
| 63.8                  | 14                             | 14 |    | 28 | 26 |    | 18 | 18 |    |    | 14 | 15 |
| 65.4                  |                                |    | 15 |    |    | 25 |    |    | 15 | 15 |    |    |
| 66.9                  | 14                             | 14 |    | 22 | 25 |    | 10 | 17 |    |    | 14 | 12 |
| 68.4                  |                                |    | 13 |    |    | 23 |    |    | 10 | 15 |    |    |
| 69.9                  | 11                             | 11 |    | 20 | 26 |    | 12 | 10 |    |    | 12 | 7  |
| 71.4                  |                                |    | 11 |    |    | 26 |    |    | 15 | 17 |    |    |
| 73.0                  | 10                             | 12 |    | 17 | 21 |    | 13 | 13 |    |    | 11 | 8  |
| 74.5                  |                                |    | 10 |    |    | 24 |    |    | 8  | 17 |    |    |
| 76.0                  | 8                              | 11 |    | 14 | 18 |    | 13 | 13 |    |    | 14 | 8  |
| 77.5                  |                                |    | 12 |    |    | 22 |    |    | 14 | 16 |    |    |
| 79.0                  | 8                              | 11 |    | 12 | 15 |    | 13 | 12 |    |    | 12 | 9  |
| 80.6                  |                                |    | 12 |    |    | 17 |    |    | 11 | 14 |    |    |
| 82.1                  | 7                              | 9  |    | 11 | 12 |    | 11 | 12 |    |    | 10 | 10 |
| 83.6                  |                                |    | 10 |    |    | 12 |    |    | 9  | 10 |    |    |
| 85.1                  | 5                              | 5  |    | 11 | 9  |    | 7  | 8  |    |    | 8  | 6  |
| 86.6                  |                                |    | 10 |    |    | 10 |    |    | 8  | 7  |    |    |
| 88.2                  | 4                              | 5  |    | 9  | 7  |    | 6  | 5  |    |    | 5  | 7  |
| 89.7                  |                                |    | 6  |    |    | 6  |    |    | 4  | 4  |    |    |
| 91.2                  | 2                              | 2  |    | 3  | 4  |    | 2  | 2  |    |    | 2  | 1  |

<sup>†</sup>Details about irrigation event listed in Table 2.2.

<sup>‡</sup>Swine lagoon liquid irrigation line at 30.4 m and the water line at 60.8 m.

<sup>§</sup>Transect location is in row numbers. Rows are 0.9 m apart.

Table A.6. Irrigation depths for July 28, 1999 for both SLL and water applications<sup>†</sup>.

| Distance <sup>‡</sup> | Transect Location <sup>§</sup> |    |    |    |    |    |    |    |    |    |    |    |    |    |
|-----------------------|--------------------------------|----|----|----|----|----|----|----|----|----|----|----|----|----|
|                       | 7                              | 10 | 13 | 16 | 17 | 20 | 23 | 27 | 33 | 36 | 40 | 43 | 44 | 47 |
| m                     | mm                             |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 0.0                   | 0                              | 0  |    |    | 0  |    | 0  | 0  | 0  | 0  | 0  |    | 0  |    |
| 1.5                   |                                |    | 1  | 1  |    | 0  |    |    |    |    |    | 0  |    | 0  |
| 3.0                   | 0                              | 2  |    |    | 2  |    | 2  | 1  | 0  | 0  | 0  |    | 0  |    |
| 4.6                   |                                |    | 5  | 5  |    | 5  |    |    |    |    |    | 0  |    | 0  |
| 6.1                   | 3                              | 7  |    |    | 8  |    | 9  | 6  | 0  | 0  | 0  |    | 0  |    |
| 7.6                   |                                |    | 11 | 11 |    | 14 |    |    |    |    |    | 0  |    | 2  |
| 9.1                   | 9                              | 12 |    |    | 13 |    | 13 | 12 | 4  | 3  | 2  |    | 1  |    |
| 10.6                  |                                |    | 16 | 15 |    | 16 |    |    |    |    |    | 3  |    | 7  |
| 12.2                  | 13                             | 15 |    |    | 16 |    | 17 | 15 | 12 | 9  | 6  |    | 5  |    |
| 13.7                  |                                |    | 16 | 16 |    | 17 |    |    |    |    |    | 8  |    | 10 |
| 15.2                  | 15                             | 16 |    |    | 17 |    | 17 | 16 | 21 | 16 | 11 |    | 10 |    |
| 16.7                  |                                |    | 17 | 16 |    | 18 |    |    |    |    |    | 11 |    | 12 |
| 18.2                  | 15                             | 15 |    |    | 15 |    | 14 | 17 | 24 | 21 | 18 |    | 10 |    |
| 19.8                  |                                |    | 16 | 14 |    | 13 |    |    |    |    |    | 12 |    | 12 |
| 21.3                  | 15                             | 16 |    |    | 11 |    | 12 | 16 | 24 | 22 | 21 |    | 8  |    |
| 22.8                  |                                |    | 12 | 11 |    | 9  |    |    |    |    |    | 12 |    | 17 |
| 24.3                  | 16                             | 15 |    |    | 9  |    | 10 | 13 | 22 | 22 | 23 |    | 9  |    |
| 25.8                  |                                |    | 14 | 13 |    | 12 |    |    |    |    |    | 15 |    | 25 |
| 27.4                  | 16                             | 17 |    |    | 18 |    | 14 | 13 | 21 | 23 | 26 |    | 15 |    |
| 28.9                  |                                |    | 14 | 18 |    | 16 |    |    |    |    |    | 22 |    | 31 |
| 30.4                  | 16                             | 17 |    |    | 19 |    | 16 | 14 | 21 | 24 | 27 |    | 26 |    |
| 31.9                  |                                |    | 15 | 18 |    | 15 |    |    |    |    |    | 22 |    | 27 |
| 33.4                  | 17                             | 17 |    |    | 17 |    | 15 | 14 | 20 | 21 | 21 |    | 17 |    |
| 35.0                  |                                |    | 17 | 16 |    | 13 |    |    |    |    |    | 18 |    | 18 |
| 36.5                  | 23                             | 17 |    |    | 15 |    | 14 | 18 | 25 | 23 | 20 |    | 16 |    |
| 38.0                  |                                |    | 22 | 17 |    | 17 |    |    |    |    |    | 15 |    | 14 |
| 39.5                  | 28                             | 28 |    |    | 16 |    | 22 | 25 | 27 | 24 | 21 |    | 11 |    |
| 41.0                  |                                |    | 32 | 20 |    | 23 |    |    |    |    |    | 15 |    | 20 |
| 42.6                  | 32                             | 37 |    |    | 22 |    | 29 | 31 | 29 | 26 | 23 |    | 14 |    |
| 44.1                  |                                |    | 40 | 29 |    | 32 |    |    |    |    |    | 18 |    | 26 |
| 45.6                  | 34                             | 39 |    |    | 30 |    | 31 | 32 | 29 | 28 | 27 |    | 19 |    |
| 47.1                  |                                |    | 39 | 31 |    | 29 |    |    |    |    |    | 22 |    | 25 |
| 48.6                  | 30                             | 37 |    |    | 31 |    | 28 | 26 | 30 | 28 | 26 |    | 21 |    |
| 50.2                  |                                |    | 32 | 31 |    | 29 |    |    |    |    |    | 21 |    | 21 |
| 51.7                  | 28                             | 31 |    |    | 31 |    | 23 | 24 | 25 | 22 | 20 |    | 20 |    |
| 53.2                  |                                |    | 25 | 28 |    | 20 |    |    |    |    |    | 18 |    | 15 |
| 54.7                  | 23                             | 27 |    |    | 28 |    | 19 | 20 | 21 | 18 | 15 |    | 17 |    |
| 56.2                  |                                |    | 20 | 21 |    | 19 |    |    |    |    |    | 17 |    | 15 |
| 57.8                  | 25                             | 26 |    |    | 16 |    | 18 | 17 | 19 | 17 | 14 |    | 18 |    |
| 59.3                  |                                |    | 17 | 16 |    | 15 |    |    |    |    |    | 20 |    | 21 |
| 60.8                  | 25                             | 19 |    |    | 17 |    | 13 | 19 | 18 | 16 | 14 |    | 27 |    |
| 62.3                  |                                |    | 20 | 16 |    | 16 |    |    |    |    |    | 25 |    | 18 |
| 63.8                  | 23                             | 23 |    |    | 16 |    | 20 | 16 | 20 | 18 | 15 |    | 29 |    |
| 65.4                  |                                |    | 17 | 16 |    | 15 |    |    |    |    |    | 22 |    | 16 |
| 66.9                  | 18                             | 20 |    |    | 16 |    | 13 | 12 | 18 | 17 | 17 |    | 20 |    |
| 68.4                  |                                |    | 18 | 17 |    | 13 |    |    |    |    |    | 17 |    | 17 |
| 69.9                  | 19                             | 19 |    |    | 18 |    | 13 | 11 | 18 | 17 | 17 |    | 15 |    |
| 71.4                  |                                |    | 21 | 19 |    | 12 |    |    |    |    |    | 15 |    | 16 |
| 73.0                  | 22                             | 23 |    |    | 19 |    | 13 | 12 | 15 | 15 | 14 |    | 16 |    |
| 74.5                  |                                |    | 21 | 20 |    | 15 |    |    |    |    |    | 15 |    | 14 |
| 76.0                  | 22                             | 22 |    |    | 20 |    | 13 | 11 | 11 | 13 | 14 |    | 14 |    |
| 77.5                  |                                |    | 20 | 17 |    | 14 |    |    |    |    |    | 13 |    | 10 |
| 79.0                  | 16                             | 17 |    |    | 15 |    | 12 | 10 | 7  | 8  | 9  |    | 12 |    |
| 80.6                  |                                |    | 14 | 13 |    | 11 |    |    |    |    |    | 8  |    | 3  |
| 82.1                  | 11                             | 11 |    |    | 10 |    | 9  | 8  | 5  | 4  | 4  |    | 5  |    |
| 83.6                  |                                |    | 6  | 7  |    | 7  |    |    |    |    |    | 4  |    | 0  |
| 85.1                  | 6                              | 5  |    |    | 4  |    | 4  | 2  | 3  | 2  | 1  |    | 1  |    |
| 86.6                  |                                |    | 2  | 2  |    | 2  |    |    |    |    |    | 0  |    | 0  |
| 88.2                  | 1                              | 1  |    |    | 1  |    | 0  | 0  | 0  | 0  | 0  |    | 0  |    |
| 89.7                  |                                |    | 0  | 0  |    | 0  |    |    |    |    |    | 0  |    | 0  |
| 91.2                  | 0                              | 0  |    |    | 0  |    | 0  | 0  | 0  | 0  | 0  |    | 0  |    |

<sup>†</sup>Details about irrigation event listed in Table 2.2.

<sup>‡</sup>Swine lagoon liquid irrigation line at 30.4 m and the water line at 60.8 m.

<sup>§</sup>Transect location is in row numbers. Rows are 0.9 m apart.



Table A.7. Irrigation depths for May 18, 2000 for water application<sup>†</sup>.

| Distance <sup>‡</sup> | Transect Location <sup>§</sup> |    |    |    |    |    |    |    |    |
|-----------------------|--------------------------------|----|----|----|----|----|----|----|----|
|                       | 50                             | 56 | 62 | 69 | 73 | 80 | 86 | 89 | 93 |
| m                     | ----- mm -----                 |    |    |    |    |    |    |    |    |
| 30.4                  | 0                              | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  |
| 33.4                  | 0                              | 0  | 0  | 1  | 2  | 2  | 1  | 0  | 0  |
| 36.5                  | 2                              | 2  | 1  | 5  | 5  | 5  | 5  | 4  | 2  |
| 39.5                  | 6                              | 5  | 5  | 7  | 10 | 11 | 11 | 10 | 8  |
| 42.6                  | 10                             | 13 | 9  | 11 | 13 | 14 | 17 | 19 | 17 |
| 45.6                  | 10                             | 16 | 15 | 16 | 14 | 19 | 22 | 25 | 24 |
| 48.6                  | 9                              | 14 | 18 | 20 | 16 | 18 | 23 | 25 | 24 |
| 51.7                  | 10                             | 15 | 20 | 23 | 19 | 18 | 22 | 24 | 22 |
| 54.7                  | 14                             | 17 | 21 | 27 | 18 | 25 | 23 | 22 | 23 |
| 57.8                  | 18                             | 21 | 21 | 25 | 19 | 24 | 25 | 22 | 27 |
| 60.8                  | 20                             | 19 | 19 | 25 | 20 | 22 | 24 | 26 | 31 |
| 63.8                  | 15                             | 14 | 18 | 20 | 20 | 24 | 26 | 22 | 27 |
| 66.9                  | 6                              | 11 | 15 | 17 | 16 | 22 | 21 | 21 | 23 |
| 69.9                  | 5                              | 10 | 12 | 14 | 16 | 19 | 21 | 22 | 23 |
| 73.0                  | 5                              | 9  | 9  | 11 | 14 | 19 | 19 | 20 | 23 |
| 76.0                  | 3                              | 6  | 5  | 7  | 9  | 13 | 14 | 16 | 18 |
| 79.0                  | 1                              | 2  | 1  | 3  | 5  | 7  | 8  | 9  | 11 |
| 82.1                  | 0                              | 0  | 0  | 1  | 2  | 4  | 4  | 4  | 4  |
| 85.1                  | 0                              | 0  | 0  | 0  | 0  | 1  | 1  | 1  | 0  |
| 88.2                  | 0                              | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  |
| 91.2                  | 0                              | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  |

<sup>†</sup>Details about irrigation event listed in Table 2.2.

<sup>‡</sup>Water line at 60.8 m.

<sup>§</sup>Transect location is in row numbers. Rows are 0.9 m apart.

Table A.8. Irrigation depths for May 19, 2000 for SLL application<sup>†</sup>.

| Distance <sup>‡</sup> | Transect Location <sup>§</sup> |    |    |    |    |    |    |    |    |
|-----------------------|--------------------------------|----|----|----|----|----|----|----|----|
|                       | 50                             | 56 | 62 | 69 | 73 | 80 | 86 | 89 | 93 |
| m                     | ----- mm -----                 |    |    |    |    |    |    |    |    |
| 0.0                   | 0                              | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  |
| 3.0                   | 0                              | 0  | 1  | 2  | 2  | 2  | 1  | 0  | 0  |
| 6.1                   | 1                              | 1  | 3  | 7  | 7  | 5  | 4  | 2  | 1  |
| 9.1                   | 4                              | 7  | 8  | 13 | 13 | 10 | 8  | 8  | 7  |
| 12.2                  | 6                              | 16 | 18 | 15 | 16 | 13 | 15 | 16 | 16 |
| 15.2                  | 9                              | 20 | 23 | 17 | 15 | 17 | 19 | 20 | 18 |
| 18.2                  | 10                             | 21 | 24 | 19 | 14 | 19 | 22 | 23 | 19 |
| 21.3                  | 12                             | 22 | 25 | 18 | 13 | 19 | 25 | 23 | 19 |
| 24.3                  | 18                             | 24 | 26 | 18 | 17 | 21 | 23 | 22 | 21 |
| 27.4                  | 24                             | 30 | 25 | 21 | 19 | 24 | 26 | 25 | 30 |
| 30.4                  | 28                             | 27 | 22 | 18 | 17 | 23 | 22 | 23 | 32 |
| 33.4                  | 17                             | 20 | 21 | 16 | 13 | 19 | 21 | 20 | 24 |
| 36.5                  | 9                              | 16 | 20 | 16 | 12 | 14 | 20 | 19 | 19 |
| 39.5                  | 6                              | 12 | 19 | 14 | 13 | 13 | 18 | 19 | 18 |
| 42.6                  | 5                              | 9  | 14 | 14 | 14 | 11 | 15 | 16 | 15 |
| 45.6                  | 3                              | 5  | 8  | 11 | 13 | 10 | 10 | 11 | 11 |
| 48.6                  | 1                              | 1  | 3  | 8  | 8  | 7  | 6  | 5  | 6  |
| 51.7                  | 0                              | 0  | 0  | 3  | 4  | 3  | 2  | 2  | 1  |
| 54.7                  | 0                              | 0  | 0  | 1  | 0  | 0  | 0  | 0  | 0  |
| 57.8                  | 0                              | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  |
| 60.8                  | 0                              | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  |

<sup>†</sup>Details about irrigation event listed in Table 2.2.

<sup>‡</sup>Swine lagoon liquid line at 30.4 m.

<sup>§</sup>Transect location is in row numbers. Rows are 0.9 m apart.

Table A.9. Irrigation depths for June 2, 2000 for SLL application<sup>†</sup>.

| Distance <sup>‡</sup> | Transect Location <sup>§</sup> |    |    |    |    |    |    |    |    |    |    |    |
|-----------------------|--------------------------------|----|----|----|----|----|----|----|----|----|----|----|
|                       | 16                             | 22 | 25 | 36 | 39 | 42 | 56 | 59 | 62 | 76 | 80 | 86 |
| m                     | ----- mm -----                 |    |    |    |    |    |    |    |    |    |    |    |
| 0.0                   | 0                              |    | 0  |    | 0  | 0  | 0  | 0  |    |    | 0  | 0  |
| 1.5                   |                                | 0  |    | 0  |    |    |    |    | 0  | 0  |    |    |
| 3.0                   | 1                              |    | 0  |    | 1  | 0  | 0  | 0  |    |    | 0  | 0  |
| 4.6                   |                                | 2  |    | 2  |    |    |    |    | 0  | 0  |    |    |
| 6.1                   | 2                              |    | 4  |    | 5  | 4  | 2  | 2  |    |    | 1  | 0  |
| 7.6                   |                                | 6  |    | 7  |    |    |    |    | 3  | 2  |    |    |
| 9.1                   | 4                              |    | 7  |    | 8  | 6  | 7  | 7  |    |    | 3  | 2  |
| 10.6                  |                                | 7  |    | 11 |    |    |    |    | 10 | 3  |    |    |
| 12.2                  | 7                              |    | 9  |    | 8  | 9  | 11 | 13 |    |    | 4  | 4  |
| 13.7                  |                                | 9  |    | 11 |    |    |    |    | 13 | 5  |    |    |
| 15.2                  | 8                              |    | 8  |    | 10 | 9  | 12 | 12 |    |    | 5  | 5  |
| 16.7                  |                                | 8  |    | 11 |    |    |    |    | 12 | 8  |    |    |
| 18.2                  | 8                              |    | 9  |    | 11 | 13 | 11 | 11 |    |    | 6  | 6  |
| 19.8                  |                                | 8  |    | 11 |    |    |    |    | 10 | 10 |    |    |
| 21.3                  | 8                              |    | 9  |    | 11 | 13 | 11 | 11 |    |    | 9  | 6  |
| 22.8                  |                                | 9  |    | 10 |    |    |    |    | 9  | 10 |    |    |
| 24.3                  | 8                              |    | 8  |    | 14 | 14 | 12 | 10 |    |    | 9  | 6  |
| 25.8                  |                                | 11 |    | 12 |    |    |    |    | 11 | 11 |    |    |
| 27.4                  | 9                              |    | 10 |    | 14 | 15 | 11 | 14 |    |    | 13 | 5  |
| 28.9                  |                                | 12 |    | 12 |    |    |    |    | 12 | 14 |    |    |
| 30.4                  | 11                             |    | 17 |    | 15 | 15 | 12 | 14 |    |    | 14 | 5  |
| 31.9                  |                                | 13 |    | 11 |    |    |    |    | 12 | 11 |    |    |
| 33.4                  | 10                             |    | 11 |    | 15 | 14 | 12 | 14 |    |    | 13 | 5  |
| 35.0                  |                                | 11 |    | 13 |    |    |    |    | 13 | 11 |    |    |
| 36.5                  | 9                              |    | 10 |    | 11 | 14 | 12 | 12 |    |    | 11 | 5  |
| 38.0                  |                                | 10 |    | 10 |    |    |    |    | 12 | 9  |    |    |
| 39.5                  | 8                              |    | 11 |    | 11 | 14 | 14 | 13 |    |    | 10 | 6  |
| 41.0                  |                                | 10 |    | 11 |    |    |    |    | 14 | 10 |    |    |
| 42.6                  | 9                              |    | 11 |    | 12 | 13 | 14 | 14 |    |    | 10 | 7  |
| 44.1                  |                                | 10 |    | 12 |    |    |    |    | 13 | 10 |    |    |
| 45.6                  | 8                              |    | 11 |    | 12 | 11 | 14 | 14 |    |    | 7  | 6  |
| 47.1                  |                                | 8  |    | 12 |    |    |    |    | 14 | 8  |    |    |
| 48.6                  | 5                              |    | 9  |    | 11 | 9  | 11 | 12 |    |    | 5  | 3  |
| 50.2                  |                                | 6  |    | 10 |    |    |    |    | 11 | 4  |    |    |
| 51.7                  | 3                              |    | 5  |    | 7  | 7  | 5  | 5  |    |    | 3  | 2  |
| 53.2                  |                                | 3  |    | 5  |    |    |    |    | 2  | 2  |    |    |
| 54.7                  | 1                              |    | 1  |    | 1  | 2  | 1  | 1  |    |    | 1  | 0  |
| 56.2                  |                                | 0  |    | 0  |    |    |    |    | 0  | 0  |    |    |
| 57.8                  | 0                              |    | 0  |    | 0  | 0  | 0  | 0  |    |    | 0  | 0  |
| 59.3                  |                                | 0  |    | 0  |    |    |    |    | 0  | 0  |    |    |
| 60.8                  | 0                              |    | 0  |    | 0  | 0  | 0  | 0  |    |    | 0  | 0  |

<sup>†</sup>Details about irrigation event listed in Table 2.2.

<sup>‡</sup>Swine lagoon liquid line at 30.4 m.

<sup>§</sup>Transect location is in row numbers. Rows are 0.9 m apart.

Table A.10. Irrigation depths for June 3, 2000 for water application<sup>†</sup>.

| Distance <sup>‡</sup> | Transect Location <sup>§</sup> |    |    |    |    |    |    |    |    |    |    |    |
|-----------------------|--------------------------------|----|----|----|----|----|----|----|----|----|----|----|
|                       | 16                             | 22 | 25 | 36 | 39 | 42 | 56 | 59 | 62 | 76 | 80 | 86 |
| m                     | ----- mm -----                 |    |    |    |    |    |    |    |    |    |    |    |
| 30.4                  | 0                              |    | 0  |    | 0  | 0  | 0  | 0  |    |    | 0  | 0  |
| 31.9                  |                                | 0  |    | 0  |    |    |    |    | 0  | 0  |    |    |
| 33.4                  | 0                              |    | 0  |    | 0  | 0  | 0  | 0  |    |    | 0  | 0  |
| 35.0                  |                                | 0  |    | 0  |    |    |    |    | 0  | 0  |    |    |
| 36.5                  | 1                              |    | 0  |    | 0  | 0  | 0  | 0  |    |    | 2  | 0  |
| 38.0                  |                                | 2  |    | 2  |    |    |    |    | 2  | 4  |    |    |
| 39.5                  | 2                              |    | 1  |    | 2  | 2  | 3  | 3  |    |    | 4  | 3  |
| 41.0                  |                                | 3  |    | 3  |    |    |    |    | 5  | 6  |    |    |
| 42.6                  | 4                              |    | 6  |    | 5  | 6  | 8  | 7  |    |    | 6  | 5  |
| 44.1                  |                                | 7  |    | 8  |    |    |    |    | 10 | 10 |    |    |
| 45.6                  | 7                              |    | 10 |    | 8  | 9  | 11 | 10 |    |    | 8  | 8  |
| 47.1                  |                                | 10 |    | 10 |    |    |    |    | 13 | 9  |    |    |
| 48.6                  | 8                              |    | 12 |    | 11 | 14 | 13 | 14 |    |    | 8  | 9  |
| 50.2                  |                                | 12 |    | 11 |    |    |    |    | 15 | 10 |    |    |
| 51.7                  | 11                             |    | 13 |    | 12 | 12 | 14 | 14 |    |    | 9  | 9  |
| 53.2                  |                                | 14 |    | 13 |    |    |    |    | 15 | 10 |    |    |
| 54.7                  | 13                             |    | 14 |    | 15 | 14 | 13 | 14 |    |    | 9  | 9  |
| 56.2                  |                                | 16 |    | 16 |    |    |    |    | 15 | 11 |    |    |
| 57.8                  | 17                             |    | 18 |    | 22 | 21 | 17 | 16 |    |    | 12 | 11 |
| 59.3                  |                                | 16 |    | 17 |    |    |    |    | 16 | 12 |    |    |
| 60.8                  | 17                             |    | 23 |    | 19 | 17 | 18 | 20 |    |    | 12 | 16 |
| 62.3                  |                                | 19 |    | 20 |    |    |    |    | 19 | 13 |    |    |
| 63.8                  | 18                             |    | 20 |    | 19 | 16 | 16 | 17 |    |    | 13 | 14 |
| 65.4                  |                                | 17 |    | 20 |    |    |    |    | 17 | 13 |    |    |
| 66.9                  | 18                             |    | 17 |    | 20 | 20 | 14 | 16 |    |    | 10 | 11 |
| 68.4                  |                                | 15 |    | 19 |    |    |    |    | 17 | 11 |    |    |
| 69.9                  | 15                             |    | 15 |    | 18 | 17 | 14 | 14 |    |    | 11 | 10 |
| 71.4                  |                                | 16 |    | 19 |    |    |    |    | 17 | 11 |    |    |
| 73.0                  | 16                             |    | 17 |    | 17 | 16 | 15 | 15 |    |    | 11 | 11 |
| 74.5                  |                                | 15 |    | 16 |    |    |    |    | 17 | 11 |    |    |
| 76.0                  | 15                             |    | 17 |    | 14 | 13 | 16 | 15 |    |    | 10 | 10 |
| 77.5                  |                                | 12 |    | 11 |    |    |    |    | 14 | 11 |    |    |
| 79.0                  | 10                             |    | 14 |    | 10 | 11 | 14 | 14 |    |    | 9  | 7  |
| 80.6                  |                                | 10 |    | 7  |    |    |    |    | 8  | 8  |    |    |
| 82.1                  | 6                              |    | 5  |    | 6  | 7  | 6  | 6  |    |    | 6  | 4  |
| 83.6                  |                                | 3  |    | 3  |    |    |    |    | 4  | 5  |    |    |
| 85.1                  | 4                              |    | 1  |    | 2  | 3  | 1  | 1  |    |    | 2  | 2  |
| 86.6                  |                                | 1  |    | 1  |    |    |    |    | 0  | 0  |    |    |
| 88.2                  | 1                              |    | 0  |    | 0  | 0  | 0  | 0  |    |    | 0  | 0  |
| 89.7                  |                                | 0  |    | 0  |    |    |    |    | 0  | 0  |    |    |
| 91.2                  | 0                              |    | 0  |    | 0  | 0  | 0  | 0  |    |    | 0  | 0  |

<sup>†</sup>Details about irrigation event listed in Table 2.2.

<sup>‡</sup>Water line at 60.8 m.

<sup>§</sup>Transect location is in row numbers. Rows are 0.9 m apart.

Table A.11. Irrigation depths for June 12, 2000 for SLL application<sup>†</sup>.

| Distance <sup>‡</sup> | Transect Location <sup>§</sup> |    |    |    |    |    |    |    |    |    |    |    |
|-----------------------|--------------------------------|----|----|----|----|----|----|----|----|----|----|----|
|                       | 16                             | 22 | 25 | 36 | 39 | 42 | 56 | 59 | 62 | 76 | 80 | 86 |
| m                     | ----- mm -----                 |    |    |    |    |    |    |    |    |    |    |    |
| 0.0                   | 1                              |    | 0  |    | 1  | 2  | 0  | 0  |    |    | 0  | 0  |
| 1.5                   |                                | 1  |    | 2  |    |    |    |    | 1  | 1  |    |    |
| 3.0                   | 2                              |    | 4  |    | 6  | 7  | 4  | 3  |    |    | 3  | 1  |
| 4.6                   |                                | 5  |    | 10 |    |    |    |    | 7  | 4  |    |    |
| 6.1                   | 5                              |    | 8  |    | 11 | 11 | 9  | 10 |    |    | 6  | 4  |
| 7.6                   |                                | 10 |    | 12 |    |    |    |    | 11 | 7  |    |    |
| 9.1                   | 8                              |    | 11 |    | 13 | 12 | 13 | 15 |    |    | 6  | 8  |
| 10.6                  |                                | 10 |    | 14 |    |    |    |    | 14 | 8  |    |    |
| 12.2                  | 10                             |    | 13 |    | 14 | 14 | 17 | 17 |    |    | 9  | 10 |
| 13.7                  |                                | 12 |    | 14 |    |    |    |    | 17 | 11 |    |    |
| 15.2                  | 12                             |    | 14 |    | 14 | 16 | 18 | 15 |    |    | 12 | 11 |
| 16.7                  |                                | 12 |    | 14 |    |    |    |    | 13 | 13 |    |    |
| 18.2                  | 14                             |    | 14 |    | 17 | 17 | 11 | 10 |    |    | 13 | 12 |
| 19.8                  |                                | 14 |    | 14 |    |    |    |    | 13 | 14 |    |    |
| 21.3                  | 14                             |    | 14 |    | 16 | 18 | 18 | 14 |    |    | 13 | 12 |
| 22.8                  |                                | 15 |    | 13 |    |    |    |    | 11 | 14 |    |    |
| 24.3                  | 13                             |    | 12 |    | 18 | 17 | 17 | 14 |    |    | 14 | 13 |
| 25.8                  |                                | 18 |    | 18 |    |    |    |    | 17 | 18 |    |    |
| 27.4                  | 15                             |    | 16 |    | 18 | 17 | 18 | 14 |    |    | 20 | 13 |
| 28.9                  |                                | 18 |    | 16 |    |    |    |    | 18 | 23 |    |    |
| 30.4                  | 15                             |    | 17 |    | 20 | 18 | 20 | 25 |    |    | 21 | 13 |
| 31.9                  |                                | 17 |    | 18 |    |    |    |    | 17 | 22 |    |    |
| 33.4                  | 14                             |    | 15 |    | 21 | 20 | 20 | 22 |    |    | 18 | 12 |
| 35.0                  |                                | 16 |    | 18 |    |    |    |    | 17 | 18 |    |    |
| 36.5                  | 13                             |    | 15 |    | 17 | 18 | 20 | 20 |    |    | 15 | 14 |
| 38.0                  |                                | 13 |    | 12 |    |    |    |    | 17 | 15 |    |    |
| 39.5                  | 12                             |    | 15 |    | 14 | 17 | 20 | 19 |    |    | 12 | 14 |
| 41.0                  |                                | 14 |    | 14 |    |    |    |    | 18 | 14 |    |    |
| 42.6                  | 12                             |    | 14 |    | 16 | 18 | 19 | 20 |    |    | 13 | 13 |
| 44.1                  |                                | 13 |    | 18 |    |    |    |    | 19 | 13 |    |    |
| 45.6                  | 10                             |    | 14 |    | 18 | 16 | 14 | 15 |    |    | 11 | 11 |
| 47.1                  |                                | 10 |    | 16 |    |    |    |    | 16 | 11 |    |    |
| 48.6                  | 6                              |    | 9  |    | 14 | 12 | 11 | 11 |    |    | 7  | 7  |
| 50.2                  |                                | 7  |    | 13 |    |    |    |    | 11 | 6  |    |    |
| 51.7                  | 3                              |    | 5  |    | 8  | 9  | 8  | 7  |    |    | 5  | 3  |
| 53.2                  |                                | 2  |    | 6  |    |    |    |    | 5  | 4  |    |    |
| 54.7                  | 1                              |    | 2  |    | 3  | 3  | 3  | 2  |    |    | 3  | 1  |
| 56.2                  |                                | 1  |    | 1  |    |    |    |    | 1  | 1  |    |    |
| 57.8                  | 0                              |    | 0  |    | 0  | 1  | 0  | 0  |    |    | 0  | 0  |
| 59.3                  |                                | 0  |    | 0  |    |    |    |    | 0  | 0  |    |    |
| 60.8                  | 0                              |    | 0  |    | 0  | 0  | 0  | 0  |    |    | 0  | 0  |

<sup>†</sup>Details about irrigation event listed in Table 2.2.

<sup>‡</sup>Swine lagoon liquid line at 30.4 m.

<sup>§</sup>Transect location is in row numbers. Rows are 0.9 m apart.

Table A.12. Irrigation depths for June 12, 2000 for water application<sup>†</sup>.

| Distance <sup>‡</sup> | Transect Location <sup>§</sup> |    |    |    |    |    |    |    |    |    |    |    |
|-----------------------|--------------------------------|----|----|----|----|----|----|----|----|----|----|----|
|                       | 16                             | 22 | 25 | 36 | 39 | 42 | 56 | 59 | 62 | 76 | 80 | 86 |
| m                     | ----- mm -----                 |    |    |    |    |    |    |    |    |    |    |    |
| 30.4                  | 0                              |    | 0  |    | 0  | 0  | 0  | 0  |    |    | 0  | 0  |
| 31.9                  |                                | 0  |    | 0  |    |    |    |    | 0  | 1  |    |    |
| 33.4                  | 0                              |    | 0  |    | 0  | 0  | 0  | 0  |    |    | 1  | 0  |
| 35.0                  |                                | 1  |    | 1  |    |    |    |    | 1  | 2  |    |    |
| 36.5                  | 5                              |    | 3  |    | 1  | 1  | 1  | 2  |    |    | 5  | 3  |
| 38.0                  |                                | 7  |    | 3  |    |    |    |    | 4  | 8  |    |    |
| 39.5                  | 8                              |    | 10 |    | 4  | 4  | 6  | 7  |    |    | 9  | 7  |
| 41.0                  |                                | 12 |    | 6  |    |    |    |    | 10 | 11 |    |    |
| 42.6                  | 12                             |    | 13 |    | 8  | 9  | 12 | 12 |    |    | 11 | 10 |
| 44.1                  |                                | 14 |    | 8  |    |    |    |    | 15 | 13 |    |    |
| 45.6                  | 16                             |    | 14 |    | 12 | 14 | 14 | 16 |    |    | 12 | 11 |
| 47.1                  |                                | 14 |    | 12 |    |    |    |    | 17 | 12 |    |    |
| 48.6                  | 17                             |    | 14 |    | 15 | 17 | 17 | 17 |    |    | 12 | 14 |
| 50.2                  |                                | 13 |    | 16 |    |    |    |    | 17 | 14 |    |    |
| 51.7                  | 16                             |    | 13 |    | 18 | 17 | 16 | 17 |    |    | 11 | 13 |
| 53.2                  |                                | 14 |    | 20 |    |    |    |    | 18 | 15 |    |    |
| 54.7                  | 16                             |    | 14 |    | 20 | 20 | 17 | 16 |    |    | 13 | 11 |
| 56.2                  |                                | 13 |    | 19 |    |    |    |    | 15 | 14 |    |    |
| 57.8                  | 30                             |    | 15 |    | 26 | 26 | 26 | 20 |    |    | 17 | 11 |
| 59.3                  |                                | 16 |    | 20 |    |    |    |    | 17 | 14 |    |    |
| 60.8                  | 20                             |    | 16 |    | 26 | 27 | 27 | 17 |    |    | 20 | 14 |
| 62.3                  |                                | 15 |    | 20 |    |    |    |    | 17 | 15 |    |    |
| 63.8                  | 21                             |    | 15 |    | 21 | 25 | 22 | 17 |    |    | 16 | 16 |
| 65.4                  |                                | 15 |    | 17 |    |    |    |    | 15 | 14 |    |    |
| 66.9                  | 17                             |    | 14 |    | 19 | 20 | 20 | 14 |    |    | 14 | 13 |
| 68.4                  |                                | 12 |    | 16 |    |    |    |    | 16 | 12 |    |    |
| 69.9                  | 13                             |    | 15 |    | 20 | 19 | 17 | 14 |    |    | 13 | 11 |
| 71.4                  |                                | 14 |    | 14 |    |    |    |    | 16 | 15 |    |    |
| 73.0                  | 15                             |    | 13 |    | 16 | 16 | 18 | 16 |    |    | 13 | 11 |
| 74.5                  |                                | 13 |    | 15 |    |    |    |    | 16 | 14 |    |    |
| 76.0                  | 12                             |    | 12 |    | 13 | 13 | 17 | 16 |    |    | 14 | 12 |
| 77.5                  |                                | 12 |    | 11 |    |    |    |    | 15 | 14 |    |    |
| 79.0                  | 9                              |    | 11 |    | 9  | 9  | 12 | 12 |    |    | 11 | 10 |
| 80.6                  |                                | 9  |    | 8  |    |    |    |    | 11 | 12 |    |    |
| 82.1                  | 6                              |    | 8  |    | 5  | 4  | 6  | 7  |    |    | 8  | 8  |
| 83.6                  |                                | 6  |    | 5  |    |    |    |    | 5  | 8  |    |    |
| 85.1                  | 3                              |    | 4  |    | 2  | 1  | 1  | 1  |    |    | 5  | 4  |
| 86.6                  |                                | 2  |    | 1  |    |    |    |    | 0  | 2  |    |    |
| 88.2                  | 1                              |    | 0  |    | 0  | 0  | 0  | 0  |    |    | 0  | 1  |
| 89.7                  |                                | 0  |    | 0  |    |    |    |    | 0  | 0  |    |    |
| 91.2                  | 0                              |    | 0  |    | 0  | 0  | 0  | 0  |    |    | 0  | 0  |

<sup>†</sup>Details about irrigation event listed in Table 2.2.

<sup>‡</sup>Water line at 60.8 m.

<sup>§</sup>Transect location is in row numbers. Rows are 0.9 m apart.

Table A.13. Irrigation depths for July 21, 2000 for SLL application<sup>†</sup>.

| Distance <sup>‡</sup> | Transect Location <sup>§</sup> |    |    |    |    |    |    |    |    |    |
|-----------------------|--------------------------------|----|----|----|----|----|----|----|----|----|
|                       | 3                              | 6  | 13 | 16 | 22 | 25 | 32 | 39 | 42 | 48 |
| m                     | ----- mm -----                 |    |    |    |    |    |    |    |    |    |
| 0.0                   |                                | 0  | 0  | 0  |    | 0  | 0  | 0  |    |    |
| 1.5                   | 0                              |    |    |    | 0  |    |    |    | 0  |    |
| 3.0                   |                                | 0  | 0  | 0  |    | 0  | 0  | 0  |    | 0  |
| 4.6                   | 0                              |    |    |    | 1  |    |    |    | 0  |    |
| 6.1                   |                                | 0  | 2  | 2  |    | 2  | 1  | 0  |    |    |
| 7.6                   | 0                              |    |    |    | 6  |    |    |    | 0  |    |
| 9.1                   |                                | 3  | 5  | 5  |    | 6  | 5  | 5  |    | 2  |
| 10.6                  | 6                              |    |    |    | 8  |    |    |    | 7  |    |
| 12.2                  |                                | 9  | 8  | 9  |    | 9  | 11 | 10 |    |    |
| 13.7                  | 11                             |    |    |    | 10 |    |    |    | 11 |    |
| 15.2                  |                                | 14 | 14 | 13 |    | 13 | 16 | 15 |    | 9  |
| 16.7                  | 14                             |    |    |    | 13 |    |    |    | 15 |    |
| 18.2                  |                                | 17 | 17 | 15 |    | 14 | 19 | 18 |    |    |
| 19.8                  | 17                             |    |    |    | 18 |    |    |    | 17 |    |
| 21.3                  |                                | 17 | 17 | 15 |    | 14 | 19 | 20 |    | 2  |
| 22.8                  | 18                             |    |    |    | 16 |    |    |    | 19 |    |
| 24.3                  |                                | 21 | 16 | 15 |    | 17 | 20 | 20 |    |    |
| 25.8                  | 25                             |    |    |    | 20 |    |    |    | 23 |    |
| 27.4                  |                                | 30 | 14 | 15 |    | 20 | 19 | 29 |    | 4  |
| 28.9                  | 32                             |    |    |    | 29 |    |    |    | 32 |    |
| 30.4                  |                                | 38 | 14 | 16 |    | 23 | 15 | 38 |    |    |
| 31.9                  | 28                             |    |    |    | 24 |    |    |    | 33 |    |
| 33.4                  |                                | 29 | 14 | 13 |    | 25 | 17 | 33 |    | 8  |
| 35.0                  | 22                             |    |    |    | 25 |    |    |    | 17 |    |
| 36.5                  |                                | 19 | 15 | 14 |    | 19 | 17 | 23 |    |    |
| 38.0                  | 16                             |    |    |    | 17 |    |    |    | 15 |    |
| 39.5                  |                                | 15 | 16 | 14 |    | 16 | 18 | 19 |    | 5  |
| 41.0                  | 14                             |    |    |    | 15 |    |    |    | 19 |    |
| 42.6                  |                                | 15 | 17 | 16 |    | 15 | 19 | 20 |    |    |
| 44.1                  | 14                             |    |    |    | 13 |    |    |    | 17 |    |
| 45.6                  |                                | 15 | 15 | 15 |    | 12 | 20 | 19 |    | 9  |
| 47.1                  | 12                             |    |    |    | 10 |    |    |    | 17 |    |
| 48.6                  |                                | 13 | 13 | 12 |    | 10 | 17 | 18 |    |    |
| 50.2                  | 9                              |    |    |    | 8  |    |    |    | 15 |    |
| 51.7                  |                                | 8  | 9  | 8  |    | 8  | 11 | 13 |    | 7  |
| 53.2                  | 5                              |    |    |    | 8  |    |    |    | 7  |    |
| 54.7                  |                                | 3  | 5  | 6  |    | 7  | 7  | 4  |    |    |
| 56.2                  | 1                              |    |    |    | 5  |    |    |    | 0  |    |
| 57.8                  |                                | 1  | 2  | 3  |    | 6  | 3  | 0  |    | 0  |
| 59.3                  | 0                              |    |    |    | 3  |    |    |    | 0  |    |
| 60.8                  |                                | 0  | 1  | 1  |    | 1  | 0  | 0  |    |    |

<sup>†</sup>Details about irrigation event listed in Table 2.2.

<sup>‡</sup>Swine lagoon liquid line at 30.4 m.

<sup>§</sup>Transect location is in row numbers. Rows are 0.9 m apart.

Table A.14. Irrigation depths for July 21, 2000 for water application<sup>†</sup>.

| Distance <sup>‡</sup> | Transect Location <sup>§</sup> |    |    |    |    |    |    |    |    |    |
|-----------------------|--------------------------------|----|----|----|----|----|----|----|----|----|
|                       | 3                              | 6  | 13 | 16 | 22 | 25 | 32 | 39 | 42 | 48 |
| m                     | ----- mm -----                 |    |    |    |    |    |    |    |    |    |
| 30.4                  |                                | 0  | 0  | 0  |    | 0  | 0  | 0  |    |    |
| 31.9                  | 0                              |    |    |    | 0  |    |    |    | 0  |    |
| 33.4                  |                                | 0  | 0  | 0  |    | 1  | 0  | 0  |    | 0  |
| 35.0                  | 0                              |    |    |    | 1  |    |    |    | 0  |    |
| 36.5                  |                                | 1  | 2  | 2  |    | 3  | 0  | 0  |    |    |
| 38.0                  | 1                              |    |    |    | 5  |    |    |    | 1  |    |
| 39.5                  |                                | 4  | 6  | 6  |    | 7  | 6  | 4  |    | 2  |
| 41.0                  | 6                              |    |    |    | 10 |    |    |    | 5  |    |
| 42.6                  |                                | 8  | 12 | 11 |    | 12 | 12 | 8  |    |    |
| 44.1                  | 10                             |    |    |    | 11 |    |    |    | 8  |    |
| 45.6                  |                                | 13 | 15 | 15 |    | 15 | 15 | 12 |    | 6  |
| 47.1                  | 12                             |    |    |    | 13 |    |    |    | 10 |    |
| 48.6                  |                                | 15 | 17 | 14 |    | 15 | 21 | 14 |    |    |
| 50.2                  | 14                             |    |    |    | 11 |    |    |    | 14 |    |
| 51.7                  |                                | 17 | 15 | 14 |    | 14 | 20 | 17 |    | 4  |
| 53.2                  | 17                             |    |    |    | 14 |    |    |    | 16 |    |
| 54.7                  |                                | 20 | 14 | 12 |    | 15 | 17 | 17 |    |    |
| 56.2                  | 24                             |    |    |    | 18 |    |    |    | 18 |    |
| 57.8                  |                                | 29 | 13 | 13 |    | 17 | 18 | 23 |    | 4  |
| 59.3                  | 34                             |    |    |    | 23 |    |    |    | 28 |    |
| 60.8                  |                                | 36 | 14 | 15 |    | 25 | 16 | 33 |    |    |
| 62.3                  | 31                             |    |    |    | 22 |    |    |    | 26 |    |
| 63.8                  |                                | 26 | 14 | 14 |    | 25 | 15 | 26 |    | 5  |
| 65.4                  | 25                             |    |    |    | 22 |    |    |    | 26 |    |
| 66.9                  |                                | 19 | 15 | 15 |    | 18 | 16 | 17 |    |    |
| 68.4                  | 16                             |    |    |    | 16 |    |    |    | 17 |    |
| 69.9                  |                                | 15 | 17 | 14 |    | 15 | 17 | 16 |    | 16 |
| 71.4                  | 14                             |    |    |    | 14 |    |    |    | 14 |    |
| 73.0                  |                                | 17 | 17 | 14 |    | 14 | 19 | 16 |    |    |
| 74.5                  | 14                             |    |    |    | 13 |    |    |    | 14 |    |
| 76.0                  |                                | 14 | 16 | 14 |    | 10 | 21 | 15 |    | 11 |
| 77.5                  | 11                             |    |    |    | 11 |    |    |    | 13 |    |
| 79.0                  |                                | 11 | 13 | 12 |    | 14 | 19 | 13 |    |    |
| 80.6                  | 8                              |    |    |    | 9  |    |    |    | 10 |    |
| 82.1                  |                                | 7  | 8  | 8  |    | 11 | 13 | 9  |    | 7  |
| 83.6                  | 2                              |    |    |    | 8  |    |    |    | 5  |    |
| 85.1                  |                                | 1  | 4  | 5  |    | 8  | 7  | 2  |    |    |
| 86.6                  | 0                              |    |    |    | 4  |    |    |    | 0  |    |
| 88.2                  |                                | 0  | 1  | 1  |    | 3  | 1  | 0  |    | 0  |
| 89.7                  | 0                              |    |    |    | 1  |    |    |    | 0  |    |
| 91.2                  |                                | 0  | 0  | 0  |    | 0  | 0  | 0  |    |    |

<sup>†</sup>Details about irrigation event listed in Table 2.2.

<sup>‡</sup>Water line at 60.8 m.

<sup>§</sup>Transect location is in row numbers. Rows are 0.9 m apart.



Table A.15. Soil inorganic N concentrations measured in the spring of 1999.

| Row <sup>†</sup> | Distance <sup>‡</sup> | NH <sub>4</sub> -N             |             |             | NO <sub>3</sub> -N |             |             |
|------------------|-----------------------|--------------------------------|-------------|-------------|--------------------|-------------|-------------|
|                  |                       | 0 – 0.3 m                      | 0.3 – 0.6 m | 0.6 – 0.9 m | 0 – 0.3 m          | 0.3 – 0.6 m | 0.6 – 0.9 m |
| #                | m                     | ----- μg g <sup>-1</sup> ----- |             |             |                    |             |             |
| 8                | 6.1                   | 0.8                            | 0.3         | 0.0         | 0.0                | 1.2         | 0.0         |
| 8                | 24.3                  | 0.4                            | 0.0         | 0.0         | 0.4                | 0.0         | 0.0         |
| 8                | 36.5                  | 0.5                            | 0.1         | 0.0         | 4.0                | 0.0         | 0.0         |
| 8                | 54.7                  | 0.1                            | 2.1         | 0.6         | 0.0                | 0.0         | 0.0         |
| 8                | 66.9                  | 0.0                            | 0.0         | 0.1         | 0.1                | 0.5         | 0.0         |
| 8                | 85.1                  | 0.0                            | 0.1         | 0.0         | 0.7                | 0.0         | 0.0         |
| 8                | 97.3                  | 0.0                            | 0.0         | 0.0         | 1.9                | 0.4         | 1.9         |
| 24               | 6.1                   | 0.3                            | 0.3         | 0.2         | 0.2                | 0.0         | 0.0         |
| 24               | 24.3                  | 0.5                            | 0.1         | 0.0         | 0.0                | 0.0         | 0.0         |
| 24               | 36.5                  | 0.2                            | 0.1         | 0.1         | 1.2                | 0.0         | 0.0         |
| 24               | 54.7                  | 0.3                            | 0.2         | 0.5         | 3.5                | 0.0         | 0.1         |
| 24               | 66.9                  | 0.0                            | 0.1         | 0.1         | 0.0                | 0.0         | 0.0         |
| 24               | 85.1                  | 0.0                            | 0.5         | 0.1         | 0.0                | 2.0         | 0.0         |
| 24               | 97.3                  | 0.0                            | 0.0         | 0.0         | 0.0                | 0.0         | 0.0         |
| 40               | 6.1                   | 0.2                            | 0.2         | 0.0         | 2.8                | 0.0         | 0.0         |
| 40               | 24.3                  | 0.5                            | 0.0         | 0.1         | 0.2                | 0.0         | 0.0         |
| 40               | 36.5                  | 0.1                            | 0.1         | 0.0         | 1.9                | 0.0         | 0.0         |
| 40               | 54.7                  | 0.4                            | 0.0         | 0.0         | 5.7                | 0.0         | 0.0         |
| 40               | 66.9                  | 0.0                            | 0.0         | 0.0         | 0.0                | 0.7         | 0.0         |
| 40               | 85.1                  | 0.0                            | 0.0         | 0.0         | 0.4                | 0.3         | 0.0         |
| 40               | 97.3                  | 0.1                            | 0.3         | 0.0         | 0.2                | 1.5         | 0.0         |
| 56               | 6.1                   | 0.3                            | 0.0         | 0.1         | 1.0                | 0.0         | 0.0         |
| 56               | 24.3                  | 0.2                            | 0.0         | 0.0         | 1.1                | 0.0         | 0.0         |
| 56               | 36.5                  | 0.0                            | 0.0         | 0.1         | 0.2                | 0.0         | 0.6         |
| 56               | 54.7                  | 0.3                            | 0.0         | 0.2         | 2.9                | 0.6         | 0.0         |
| 56               | 66.9                  | 0.0                            | 0.0         | 0.2         | 0.0                | 0.0         | 0.0         |
| 56               | 85.1                  | 0.3                            | 0.1         | 0.0         | 0.9                | 0.0         | 0.0         |
| 56               | 97.3                  | 0.4                            | 1.6         | 0.1         | 2.4                | 1.2         | 0.0         |
| 72               | 6.1                   | 0.0                            | 0.0         | 0.0         | 1.2                | 0.0         | 0.0         |
| 72               | 24.3                  | 0.0                            | 0.0         | 0.0         | 0.3                | 0.0         | 0.0         |
| 72               | 36.5                  | 0.4                            | 0.8         | 0.0         | 0.0                | 0.0         | 0.0         |
| 72               | 54.7                  | 0.1                            | 0.1         | 0.1         | 2.8                | 0.1         | 0.0         |
| 72               | 66.9                  | 0.3                            | 2.1         | 0.3         | 0.1                | 1.0         | 0.4         |
| 72               | 85.1                  | 0.0                            | 0.3         | 0.1         | 2.3                | 1.5         | 1.7         |
| 72               | 97.3                  | 0.0                            | 0.2         | 0.0         | 0.6                | 0.0         | 0.0         |
| 88               | 6.1                   | 0.4                            | 0.0         | 0.0         | 3.8                | 0.0         | 0.0         |
| 88               | 24.3                  | 0.1                            | 0.0         | 0.0         | 3.1                | 0.0         | 0.0         |
| 88               | 36.5                  | 0.3                            | 0.2         | 0.0         | 2.5                | 0.0         | 0.0         |
| 88               | 54.7                  | 6.4                            | 1.2         | 1.8         | 3.9                | 1.9         | 1.0         |
| 88               | 66.9                  | 0.6                            | 0.0         | 0.0         | 4.6                | 0.0         | 1.1         |
| 88               | 85.1                  | 0.1                            | 0.0         | 0.0         | 2.0                | 0.0         | 1.1         |
| 88               | 97.3                  | 1.4                            | 0.4         | 0.6         | 0.2                | 1.4         | 0.0         |

<sup>†</sup> Rows 0 to 48 were planted in soybean and rows 49 to 96 were planted in corn.

<sup>‡</sup> Distance was measured starting at 0 m in Section 1 with the SLL irrigation line located at 30.4 m. The water irrigation line was located at 60.8 m. See Figure 2.2 for plot design.

Table A.16. Soil inorganic N concentrations measured in the fall of 1999.

| Row <sup>†</sup> | Distance <sup>‡</sup> | Applied<br>N        | NH <sub>4</sub> -N             |             |             | NO <sub>3</sub> -N |             |             |
|------------------|-----------------------|---------------------|--------------------------------|-------------|-------------|--------------------|-------------|-------------|
|                  |                       |                     | 0 – 0.3 m                      | 0.3 – 0.6 m | 0.6 – 0.9 m | 0 – 0.3 m          | 0.3 – 0.6 m | 0.6 – 0.9 m |
| #                | m                     | kg ha <sup>-1</sup> | ----- µg g <sup>-1</sup> ----- |             |             |                    |             |             |
| 9                | 76.0                  | 56                  | 3.0                            | 2.7         | 2.4         | 1.4                | 0.9         | 0.8         |
| 16               | 76.0                  | 224                 | 2.8                            | 2.8         | 3.5         | 2.8                | 2.5         | 3.7         |
| 24               | 76.0                  | 168                 | 1.8                            | 2.4         | 3.2         | 1.1                | 1.2         | 1.1         |
| 36               | 0.0                   | 2                   | 4.4                            | 1.1         | 1.5         | 1.0                | 0.3         | 0.7         |
| 36               | 6.1                   | 42                  | 1.8                            | 1.7         | 1.0         | 1.6                | 0.8         | 0.4         |
| 36               | 12.2                  | 141                 | 1.5                            | 1.4         | 1.0         | 1.9                | 0.9         | 0.2         |
| 36               | 18.2                  | 238                 | 1.7                            | 1.8         | 1.4         | 3.6                | 0.9         | 0.3         |
| 36               | 24.3                  | 253                 | 1.0                            | 0.3         | 0.2         | 2.1                | 1.3         | 0.6         |
| 36               | 30.4                  | 263                 | 0.5                            | 3.7         | 0.7         | 3.5                | 2.3         | 3.5         |
| 36               | 36.5                  | 253                 | 0.7                            | 0.2         | 0.6         | 3.4                | 1.4         | 2.1         |
| 36               | 42.6                  | 226                 | 0.6                            | 0.5         | 0.7         | 0.7                | 1.1         | 1.7         |
| 36               | 48.6                  | 197                 | 0.8                            | 0.5         | 0.5         | 1.3                | 1.6         | 0.9         |
| 36               | 54.7                  | 97                  | 0.8                            | 0.6         | 2.1         | 2.0                | 1.1         | 1.6         |
| 36               | 60.8                  | 13                  | 2.2                            | 0.8         | 0.9         | 1.7                | 1.3         | 0.8         |
| 36               | 76.0                  | 112                 | 1.8                            | 4.5         | 2.4         | 0.5                | 0.8         | 1.3         |
| 43               | 76.0                  | 0                   | 0.5                            | 0.4         | 0.9         | 0.3                | 0.1         | 1.0         |
| 54               | 76.0                  | 112                 | 1.0                            | 1.4         | 0.9         | 0.9                | 1.3         | 2.7         |
| 63               | 76.0                  | 168                 | 0.6                            | 0.9         | 0.9         | 0.4                | 2.2         | 3.6         |
| 70               | 1.5                   | 3                   | 0.6                            | 0.1         | 0.0         | 1.2                | 0.4         | 0.2         |
| 70               | 7.6                   | 45                  | 0.8                            | 0.3         | 0.2         | 1.0                | 0.9         | 0.2         |
| 70               | 13.7                  | 123                 | 0.6                            | 0.4         | 0.0         | 0.9                | 0.4         | 0.1         |
| 70               | 19.8                  | 147                 | 1.4                            | 0.3         | 0.1         | 1.4                | 0.5         | 0.0         |
| 70               | 25.8                  | 164                 | 0.5                            | 0.4         | 0.4         | 0.7                | 0.1         | 0.1         |
| 70               | 31.9                  | 215                 | 1.5                            | 0.3         | 0.0         | 1.9                | 0.5         | 0.6         |
| 70               | 38.0                  | 149                 | 0.7                            | 0.6         | 0.2         | 1.2                | 0.6         | 2.9         |
| 70               | 44.1                  | 157                 | 1.2                            | 0.3         | 0.6         | 1.4                | 1.0         | 2.8         |
| 70               | 50.2                  | 138                 | 8.3                            | 0.4         | 0.5         | 1.7                | 1.6         | 3.3         |
| 70               | 56.2                  | 52                  | 1.4                            | 1.9         | 0.8         | 2.1                | 1.6         | 2.9         |
| 70               | 59.3                  | 23                  | 0.8                            | 0.6         | 0.8         | 1.2                | 1.4         | 2.8         |
| 70               | 76.0                  | 224                 | 6.5                            | 0.7         | 0.3         | 2.8                | 6.7         | 8.5         |
| 83               | 76.0                  | 0                   | 0.6                            | 0.6         | 0.9         | 3.7                | 1.9         | 0.9         |
| 91               | 76.0                  | 56                  | 1.0                            | 0.5         | 0.9         | 1.4                | 1.9         | 4.4         |

<sup>†</sup> Rows 0 to 48 were planted in soybean and rows 49 to 96 were planted in corn.

<sup>‡</sup> Distance was measured starting at 0 m in Section 1 with the SLL irrigation line located at 30.4 m. The water irrigation line was located at 60.8 m. See Figure 2.2 for plot design. Soil samples for the fertilizer treatments are specified at 76.0 m.

Table A.17. Soil inorganic N concentrations measured in the spring of 2000.

| Row <sup>†</sup> | Distance <sup>‡</sup> | NH <sub>4</sub> -N             |             |             | NO <sub>3</sub> -N |             |             |
|------------------|-----------------------|--------------------------------|-------------|-------------|--------------------|-------------|-------------|
|                  |                       | 0 – 0.3 m                      | 0.3 – 0.6 m | 0.6 – 0.9 m | 0 – 0.3 m          | 0.3 – 0.6 m | 0.6 – 0.9 m |
| #                | m                     | ----- µg g <sup>-1</sup> ----- |             |             |                    |             |             |
| 9                | 76.0                  | 2.6                            | 1.3         | 2.5         | 0.6                | 1.6         | 2.0         |
| 16               | 76.0                  | 3.8                            | 1.0         | 2.2         | 1.2                | 1.9         | 3.2         |
| 24               | 76.0                  | 1.7                            | 1.2         | 0.8         | 0.6                | 1.1         | 1.4         |
| 36               | 0.0                   | 1.9                            | 0.8         | 1.4         | 0.5                | 0.4         | 1.0         |
| 36               | 3.0                   | 1.8                            | 1.7         | 0.7         | 0.2                | 0.2         | 1.3         |
| 36               | 6.1                   | 2.0                            | 1.0         | 0.8         | 0.2                | 0.2         | 0.2         |
| 36               | 9.1                   | 5.7                            | 1.6         | 0.7         | 0.6                | 0.6         | 0.3         |
| 36               | 12.2                  | 2.9                            | 1.2         | 0.7         | 0.3                | 0.2         | 0.2         |
| 36               | 15.2                  | 2.0                            | 1.1         | 0.6         | 0.2                | 0.4         | 0.6         |
| 36               | 18.2                  | 2.2                            | 0.7         | 0.8         | 0.2                | 0.5         | 1.2         |
| 36               | 21.3                  | 2.2                            | 1.0         | 1.0         | 0.4                | 0.5         | 0.3         |
| 36               | 24.3                  | 2.3                            | 1.3         | 1.2         | 0.4                | 0.6         | 0.9         |
| 36               | 27.4                  | 2.3                            | 1.1         | 1.6         | 0.5                | 0.4         | 2.6         |
| 36               | 30.4                  | 5.7                            | 1.1         | 1.2         | 1.4                | 2.1         | 3.6         |
| 36               | 33.4                  | 1.8                            | 1.0         | 1.1         | 0.6                | 0.4         | 1.2         |
| 36               | 36.5                  | 2.1                            | 1.6         | 2.5         | 0.7                | 2.1         | 3.4         |
| 36               | 39.5                  | 1.7                            | 1.5         | 2.6         | 0.5                | 2.1         | 3.2         |
| 36               | 42.6                  | 2.4                            | 1.5         | 1.6         | 1.2                | 1.8         | 2.5         |
| 36               | 45.6                  | 2.4                            | 1.0         | 1.2         | 0.4                | 0.4         | 1.2         |
| 36               | 48.6                  | 2.8                            | 1.6         | 1.0         | 0.8                | 1.4         | 1.6         |
| 36               | 51.7                  | 2.8                            | 1.0         | 0.4         | 0.8                | 1.2         | 1.6         |
| 36               | 54.7                  | 1.7                            | 0.4         | 1.2         | 0.7                | 0.6         | 1.7         |
| 36               | 57.8                  | 2.2                            | 0.9         | 1.6         | 0.4                | 0.4         | 1.4         |
| 36               | 60.8                  | 2.0                            | 1.0         | 1.3         | 0.4                | 1.4         | 1.8         |
| 36               | 76.0                  | 2.1                            | 1.5         | 1.1         | 0.4                | 0.9         | 0.9         |
| 43               | 76.0                  | 1.6                            | 0.6         | 0.6         | 0.5                | 0.9         | 1.4         |
| 54               | 76.0                  | 2.2                            | 1.1         | 1.1         | 0.4                | 0.9         | 0.2         |
| 63               | 76.0                  | 2.3                            | 1.6         | 1.2         | 0.4                | 2.6         | 2.8         |
| 70               | 0.0                   | 2.0                            | 1.0         | 0.6         | 0.7                | 1.0         | 0.2         |
| 70               | 3.0                   | 3.4                            | 1.2         | 2.1         | 1.0                | 0.4         | 1.0         |
| 70               | 6.1                   | 3.0                            | 2.9         | 1.2         | 1.1                | 0.7         | 1.2         |
| 70               | 9.1                   | 2.8                            | 1.2         | 1.0         | 1.0                | 0.6         | 1.0         |
| 70               | 12.2                  | 2.8                            | 1.5         | 1.2         | 1.1                | 0.7         | 1.3         |
| 70               | 15.2                  | 3.0                            | 1.1         | 0.6         | 1.4                | 1.0         | 1.2         |
| 70               | 18.2                  | 1.8                            | 0.9         | 0.9         | 0.2                | 0.2         | 0.2         |
| 70               | 21.3                  | 4.1                            | 1.2         | 0.6         | 1.7                | 0.5         | 0.4         |
| 70               | 24.3                  | 2.2                            | 1.1         | 2.1         | 1.0                | 0.8         | 1.4         |
| 70               | 27.4                  | 2.3                            | 1.5         | 0.9         | 1.1                | 1.8         | 0.3         |
| 70               | 30.4                  | 2.4                            | 1.0         | 0.7         | 1.4                | 1.0         | 0.4         |
| 70               | 33.4                  | 2.9                            | 1.2         | 0.5         | 1.2                | 0.9         | 0.3         |
| 70               | 36.5                  | 8.8                            | 0.8         | 0.5         | 0.7                | 0.7         | 0.4         |
| 70               | 39.5                  | 2.2                            | 1.0         | 1.2         | 1.4                | 1.2         | 1.9         |
| 70               | 42.6                  | 2.6                            | 0.8         | 1.6         | 0.3                | 0.2         | 1.8         |
| 70               | 45.6                  | 4.5                            | 1.6         | 1.6         | 1.8                | 1.3         | 2.6         |
| 70               | 48.6                  | 2.3                            | 1.0         | 1.8         | 0.4                | 1.4         | 2.7         |
| 70               | 51.7                  | 4.8                            | 0.9         | 1.0         | 1.6                | 1.8         | 2.1         |
| 70               | 54.7                  | 2.5                            | 1.3         | 1.6         | 0.5                | 1.7         | 3.1         |
| 70               | 57.8                  | 2.8                            | 0.8         | 1.5         | 0.3                | 0.6         | 2.6         |
| 70               | 60.8                  | 2.0                            | 1.6         | 2.3         | 3.1                | 1.9         | 2.8         |
| 72               | 76.0                  | 3.4                            | 2.5         | 1.8         | 0.6                | 2.8         | 4.0         |
| 83               | 76.0                  | 2.5                            | 1.4         | 0.9         | 1.0                | 1.8         | 3.2         |
| 90               | 76.0                  | 3.0                            | 1.1         | 1.4         | 1.0                | 2.1         | 3.0         |

<sup>†</sup> Rows 0 to 48 were planted in soybean and rows 49 to 96 were planted in corn.

<sup>‡</sup> Distance was measured starting at 0 m in Section 1 with the SLL irrigation line located at 30.4 m. The water irrigation line was located at 60.8 m. See Figure 2.2 for plot design. Soil samples for the fertilizer treatments are specified at 76.0 m.

Table A.18. Soil inorganic N concentrations measured in the fall of 2000.

| Row <sup>†</sup> | Distance <sup>‡</sup> | Applied<br>N        | NH <sub>4</sub> -N |             |             | NO <sub>3</sub> -N |             |             |
|------------------|-----------------------|---------------------|--------------------|-------------|-------------|--------------------|-------------|-------------|
|                  |                       |                     | 0 – 0.3 m          | 0.3 – 0.6 m | 0.6 – 0.9 m | 0 – 0.3 m          | 0.3 – 0.6 m | 0.6 – 0.9 m |
| #                | m                     | kg ha <sup>-1</sup> | μg g <sup>-1</sup> |             |             |                    |             |             |
| 7                | 76.0                  | 56                  | 1.2                | 1.0         | 1.3         | 5.1                | 3.8         | 2.4         |
| 14               | 76.0                  | 224                 | 2.2                | 0.8         | 1.4         | 6.8                | 5.3         | 5.3         |
| 16               | 0.0                   | 3                   | 0.7                | 0.6         | 0.8         | 2.5                | 4.6         | 4.2         |
| 16               | 3.0                   | 30                  | 0.7                | 0.5         | 0.8         | 2.8                | 2.4         | 2.3         |
| 16               | 6.1                   | 73                  | 1.6                | 1.7         | 2.0         | 3.5                | 5.2         | 2.4         |
| 16               | 9.1                   | 114                 | 3.7                | 1.0         | 1.9         | 4.7                | 3.9         | 2.4         |
| 16               | 12.2                  | 143                 | 1.3                | 1.0         | 0.7         | 5.0                | 2.8         | 2.5         |
| 16               | 15.2                  | 160                 | 2.1                | 0.8         | 0.6         | 7.6                | 4.8         | 2.6         |
| 16               | 18.2                  | 170                 | 1.7                | 1.0         | 0.5         | 4.4                | 3.3         | 2.0         |
| 16               | 21.3                  | 172                 | 0.8                | 0.6         | 1.8         | 4.7                | 4.4         | 3.0         |
| 16               | 24.3                  | 190                 | 1.2                | 1.7         | 1.9         | 5.7                | 3.6         | 2.3         |
| 16               | 27.4                  | 212                 | 1.9                | 0.7         | 1.3         | 5.4                | 3.3         | 2.8         |
| 16               | 30.4                  | 218                 | 1.2                | 0.7         | 0.9         | 6.7                | 5.1         | 4.2         |
| 16               | 33.4                  | 221                 | 1.2                | 0.8         | 0.8         | 3.9                | 2.4         | 2.1         |
| 16               | 36.5                  | 194                 | 1.2                | 1.0         | 1.3         | 4.3                | 2.6         | 1.8         |
| 16               | 39.5                  | 172                 | 1.0                | 1.5         | 1.2         | 4.8                | 2.4         | 2.1         |
| 16               | 42.6                  | 188                 | 1.1                | 1.5         | 0.9         | 5.1                | 3.4         | 2.2         |
| 16               | 45.6                  | 194                 | 1.0                | 1.0         | 1.0         | 5.0                | 3.5         | 2.1         |
| 16               | 48.6                  | 171                 | 0.8                | 1.4         | 1.4         | 1.9                | 2.2         | 1.5         |
| 16               | 51.7                  | 116                 | 0.9                | 1.4         | 0.7         | 2.1                | 2.5         | 1.8         |
| 16               | 54.7                  | 48                  | 1.2                | 1.1         | 1.0         | 5.1                | 4.2         | 1.7         |
| 16               | 57.8                  | 10                  | 1.2                | 1.0         | 1.0         | 4.1                | 4.0         | 2.2         |
| 22               | 1.5                   | 6                   | 1.1                | 0.6         | 0.8         | 3.0                | 2.5         | 1.4         |
| 22               | 4.6                   | 33                  | 1.0                | 0.6         | 0.7         | 2.6                | 1.3         | 1.2         |
| 22               | 10.6                  | 103                 | 0.7                | 1.2         | 1.2         | 3.2                | 2.2         | 1.0         |
| 22               | 16.7                  | 133                 | 1.2                | 1.2         | 0.9         | 4.1                | 2.7         | 1.5         |
| 22               | 22.8                  | 160                 | 1.6                | 1.1         | 0.8         | 2.8                | 2.7         | 1.5         |
| 22               | 28.9                  | 227                 | 1.6                | 1.0         | -           | 3.9                | 1.8         | -           |
| 22               | 31.9                  | 212                 | 1.4                | 0.9         | 1.7         | 3.3                | 2.3         | 1.4         |
| 22               | 35.0                  | 205                 | 1.4                | 1.2         | 1.3         | 3.0                | 1.7         | 2.2         |
| 22               | 41.0                  | 160                 | 0.9                | 1.1         | 1.3         | 1.9                | 2.1         | 1.7         |
| 22               | 47.1                  | 114                 | 1.6                | 0.7         | 0.7         | 2.1                | 1.0         | 0.7         |
| 22               | 53.2                  | 48                  | 1.8                | 1.0         | 0.9         | 2.3                | 1.6         | 1.4         |
| 22               | 59.3                  | 10                  | 1.2                | 1.0         | 1.6         | 2.5                | 1.2         | 0.7         |
| 22               | 92.0                  | 168                 | 1.5                | 1.0         | 0.8         | 2.0                | 1.2         | 1.0         |
| 22               | 97.0                  | 112                 | 0.6                | 0.6         | 1.3         | 0.8                | 1.7         | 1.4         |
| 22               | 102.0                 | 56                  | 1.2                | 1.4         | 1.1         | 1.6                | 4.5         | 2.3         |

<sup>†</sup> Rows 0 to 48 were planted in soybean and rows 49 to 96 were planted in corn. Row 22 was the nonnodulating soybean isolate.

<sup>‡</sup> Distance was measured starting at 0 m in Section 1 with the SLL irrigation line located at 30.4 m. The water irrigation line was located at 60.8 m. See Figure 2.2 for plot design. Soil samples for the fertilizer treatments are specified at 76.0 m. The fertilizer treatments for the nonnodulating soybean started at distance 92.0 m.

Table A.18. Continued.

| Row <sup>†</sup> | Distance <sup>‡</sup> | Applied N           | NH <sub>4</sub> -N |             |             | NO <sub>3</sub> -N |             |             |
|------------------|-----------------------|---------------------|--------------------|-------------|-------------|--------------------|-------------|-------------|
|                  |                       |                     | 0 – 0.3 m          | 0.3 – 0.6 m | 0.6 – 0.9 m | 0 – 0.3 m          | 0.3 – 0.6 m | 0.6 – 0.9 m |
| #                | m                     | kg ha <sup>-1</sup> | μg g <sup>-1</sup> |             |             |                    |             |             |
| 22               | 107.0                 | 224                 | 0.9                | 0.9         | 1.2         | 2.5                | 1.9         | 2.1         |
| 22               | 112.0                 | 0                   | 0.9                | 1.1         | 0.6         | 2.3                | 3.2         | 2.1         |
| 28               | 76.0                  | 168                 | 1.1                | 0.8         | 0.6         | 4.4                | 4.6         | 6.1         |
| 36               | 76.0                  | 112                 | 0.8                | 0.5         | 0.7         | 4.6                | 2.2         | 1.9         |
| 44               | 76.0                  | 0                   | 2.1                | 0.7         | 1.2         | 2.7                | 3.1         | 3.2         |
| 56               | 76.0                  | 112                 | 0.6                | 0.9         | 0.4         | 0.2                | 0.6         | 1.0         |
| 62               | 1.5                   | 5                   | 1.3                | 1.3         | 0.9         | 0.8                | 0.5         | 0.7         |
| 62               | 4.6                   | 41                  | 1.4                | 1.2         | 2.0         | 1.5                | 1.4         | 0.5         |
| 62               | 7.6                   | 90                  | 1.9                | 1.3         | 1.7         | 1.1                | 0.6         | 0.7         |
| 62               | 10.6                  | 177                 | 0.8                | 0.7         | 1.6         | 1.3                | 0.8         | 1.5         |
| 62               | 13.7                  | 238                 | 1.0                | 0.2         | 0.5         | 1.9                | 0.8         | 2.6         |
| 62               | 16.7                  | 233                 | 0.3                | 0.6         | 0.0         | 1.5                | 2.2         | 2.0         |
| 62               | 19.8                  | 233                 | 0.3                | 1.1         | 0.0         | 1.7                | 1.6         | 1.8         |
| 62               | 22.8                  | 224                 | 0.4                | 0.5         | 0.6         | 2.3                | 1.9         | 2.4         |
| 62               | 25.8                  | 257                 | 0.4                | 0.2         | 0.3         | 2.1                | 3.0         | 2.4         |
| 62               | 28.9                  | 258                 | 0.9                | 0.8         | 1.9         | 1.5                | 2.3         | 2.3         |
| 62               | 31.9                  | 242                 | 1.0                | 0.7         | 0.9         | 1.9                | 4.9         | 3.7         |
| 62               | 35.0                  | 239                 | 1.3                | 1.1         | 1.3         | 0.9                | 3.3         | 3.2         |
| 62               | 38.0                  | 227                 | 1.1                | 0.9         | 1.0         | 1.4                | 2.0         | 2.3         |
| 62               | 41.0                  | 230                 | 0.6                | 0.4         | 0.6         | 1.2                | 1.3         | 1.0         |
| 62               | 44.1                  | 198                 | 0.7                | 0.1         | 0.4         | 1.9                | 1.0         | 1.6         |
| 62               | 47.1                  | 159                 | 1.3                | 1.0         | 0.4         | 1.4                | 1.1         | 3.0         |
| 62               | 50.2                  | 102                 | 1.3                | 0.8         | 0.8         | 1.2                | 0.7         | 1.6         |
| 62               | 53.2                  | 30                  | 1.1                | 0.4         | 0.7         | 0.8                | 0.7         | 1.4         |
| 62               | 56.2                  | 4                   | 0.7                | 1.2         | 1.3         | 0.2                | 1.2         | 1.6         |
| 62               | 59.3                  | 0                   | 0.8                | 1.2         | 0.6         | 0.7                | 0.7         | 1.6         |
| 64               | 76.0                  | 168                 | 0.9                | 1.0         | 0.4         | 0.6                | 0.7         | 1.5         |
| 73               | 76.0                  | 224                 | 0.5                | 0.8         | 0.8         | 1.6                | 10.1        | 5.6         |
| 82               | 76.0                  | 0                   | 0.7                | 0.6         | 0.9         | 0.8                | 0.6         | 2.3         |
| 92               | 76.0                  | 56                  | 0.7                | 0.5         | 0.9         | 0.3                | 0.3         | 1.2         |

<sup>†</sup> Rows 0 to 48 were planted in soybean and rows 49 to 96 were planted in corn. Row 22 was the nonnodulating soybean isolate.

<sup>‡</sup> Distance was measured starting at 0 m in Section 1 with the SLL irrigation line located at 30.4 m. The water irrigation line was located at 60.8 m. See Figure 2.2 for plot design. Soil samples for the fertilizer treatments are specified at 76.0 m. The fertilizer treatments for the nonnodulating soybean started at distance 92.0 m.